CONFERENCE PRE-PRINT

RECENT EXPERIMENTS AND DEVELOPMENT OF LHCD SYSTEM ON HL-3

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Abstract

On HL-3, former named HL-2M [1,2], 2 MW LHCD system has been installed and demonstrated. The coupled power reached 1MW with coupling coefficient 95% in 2025. Gas injection next to the antenna was applied for the coupling optimization, which is effective in the experiments. Full non-inductive current drive phenomenon was also obtained in the experiments, where 300 kA plasma current was driven by 800kW coupled LH power. For D-T phase, the ability of HL-3 LHCD system will be upgrade to 4MW. 4 more klystrons will be installed and new mode converters will be applied in the transmission lines to avoid high insertion loss on the long transmission lines. Two new antennas have been designed with the peak parallel refractive indexes $N_{//0}$ around 2.0 until now, which will be manufactured soon.

1. INTRODUCTION

As the most effective method of current drive, Lower Hybrid Current Drive (LHCD) is widely used in tokamaks [3,4,5,6]. HL-3 is a tokamak of SWIP located in Chengdu, China, where 1 MA plasma current was realized at the end of 2021 after one year device upgraded to divertor configuration since the first plasma at the end of 2020 [7]. 19.5 MW heating and current drive systems including 12 MW Neutral Beam Injection (NBI), 5.5 MW Electron Cyclotron Resonance Heating (ECRH) and 2 MW LHCD system, have been developed on HL-3 since 2023. With the powerful heating systems, more high performance plasma has been obtained since 2023, when the systems were constructed. The heating systems are on upgrading to 41 MW power capacity, not only including a new 7 MW NBI beam line and a new 6 MW Ion Cyclotron Resonance Heating (ICRH) system, but also improving the original NBI beam lines, ECRH and LHCD system, as shown in TABLE 1.

TABLE 1. MAIN PARAMETERS of HL-3

Ip	R	a	R/a	κ	δ	Bt	NBI	ECRH	ICRH	LHCD
3 MA	1.78 m	0.65 m	3.6	1.8	0.5	3 T	12→20 MW	5.5→11 MW	0→6 MW	2→4 MW

This paper introduces the constructed LHCD system and its demonstration experiments. In addition, the upgradation of the LHCD system is briefly introduced.

2. LHCD SYSTEM OF HL-3

The 2 MW / 3.7 GHz /3s LHCD system consisting of microwave source system, transmission line system and antenna system was designed in 2017 [8], commissioned in 2022 and installed in 2023. The power in single WaveGuide (WG) increased to 490 kW and the coupled power reached 1 MW in 2025, indicating that the WG and the antenna were well practiced by high Lower Hybrid Wave (LHW) power. The development of LHCD system on HL-3 is shown below in FIG. 1.

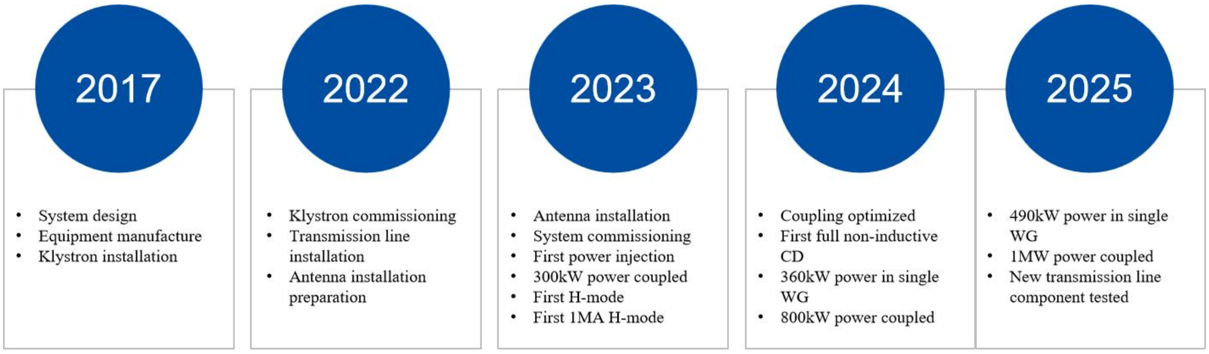

FIG. 1. Development of LHCD system on HL-3

The wave power is generated by four klystrons located far from the tokamak, transmitted through 40-meter-long transmission lines and then launched to the plasma via a Full Active Multijunction (FAM) concept antenna.

2.1. Microwave source system

Four TH2103C-1 type klystrons made by THALES company, each output power capacity of which is 500 kW / 3.7 GHz / 3 s, were installed in the Radio Frequency (RF) heating hall of SWIP, as shown in FIG. 2. The klystron outputs power via 2 arms with 250 kW each, which is recombined by a power re-combiner, making the transmission line transmit 500 kW LHW power The corresponding equipment was installed to the klystrons, including the magnets, oil tanks, auxiliary power supplies, exciting source, cathode high-voltage power supplies, Programmable Logic Controller (PLC) system, timing control system, water cooling system and protection system, etc.

FIG. 2. The Klystrons installed in the RF heating hall

The corresponding magnet with 4 groups coils, supplied by 3 magnet power supplies, was installed on the oil tank. The klystron was installed in the magnet, with the cathode into the oil tank. In the oil tank, the filament power supply gives 200 W heating power to the filament, isolated by a high voltage transformer. The PLC system controls the LHCD system via equipment status. The timing control system gives the activation command to the different equipment in a certain order in accordance with the system operation requirements. The water cooling system supplies deionized water to cool the equipment from operation heat. The protection system can shut the cathode high-voltage power supply down in 10 micro second after receive an error signal, which would prevent damage of the important equipment.

2.2. Transmission lines

The transmission line is used to transmit high-power microwaves from the wave source to the launcher, serving as a crucial component of the LHCD system. The transmission capacity, microwave transmission characteristics, and transmission efficiency of the transmission line affect the stability and reliability of the entire system.

The klystron of HL-3 LHCD system features dual-window output configuration, four of which give eight output ports. The re-combiner recombines the power from one klystron and generate a single 500 kW power transmission line. At the antenna side, 3-dB power divider is implemented, creating eight WG channels connected to the back flange of the antenna. This configuration forms four independent transmission lines, each about 40-meter long. The transmission line assembled the function of arc detection and power monitoring to track operational status of the system. The transmission lines are filled by nitrogen gas maintaining a pressure of 0.3 MPa (external pressure: 0.2 MPa).

The transmission line goes across from the RF heating hall to HL-3 hall, shown in FIG. 3, mainly composed of WG components based on BJ32 standard square WG, including straight WG, bend, arc detection WG, pumping and gas injection WG, circulator, DC break, high-power water load, power combiner, 3-dB power divider, directional coupler and ceramic window, etc.

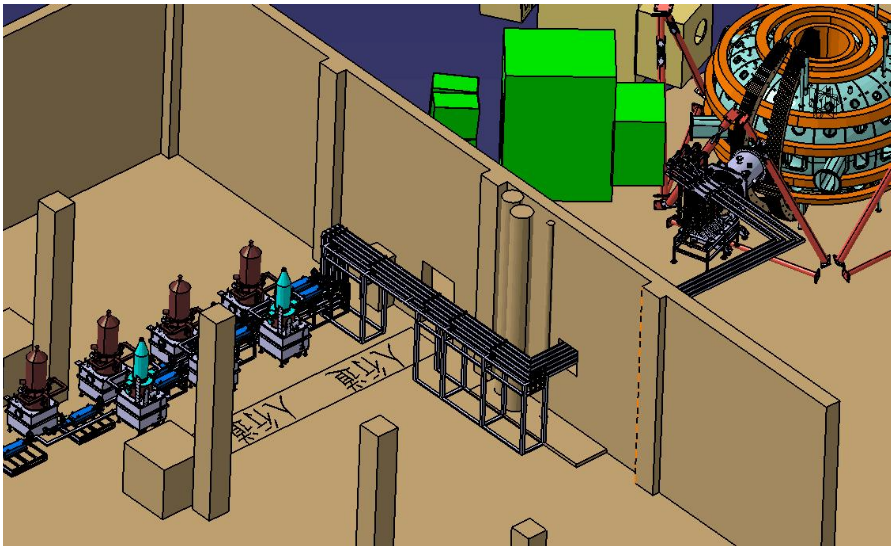

FIG. 3. The LHCD transmission lines distribution in the RF heating hall and HL-3 hall

The power status on the transmission line is monitored in real time by the power measurement system. A directional coupler is used to obtain a certain proportion of low power microwave signals on the transmission line. The voltage can be read by the microwave power measurement equipment, based on which the transmitted and reflected power can be obtained. The reflected power is monitored. If it is found that the reflected power on the klystron side was too high, the protection system would work and shut down the cathode power supply. On the other hand, if the reflected power on the antenna side was too high, the amplifier of the exciting source would be shut down for 3.6 ms, and then start up again, increasing the commissioning efficiency much.

2.3. Antenna system

The LHCD antenna of HL-3 utilizes a 450mm×500mm middle-plane port on the machine to inject the power to plasma from Low Field Side (LFS). The power spectrum of the antenna can be supplied and controlled in a requirement range. The antenna is also movable on radial direction, which gives improvement ability on LH coupling.

The 4 MW FAM concept antenna was installed and demonstrated, consisting of 6×32 grills, with passive ones at each side [7], shown in FIG. 4. 1-3 power divider in poloidal direction based on TE10-TE30 mode converter is used for 6-row realization. The peak refractive index is designed as $n_{\|0}$=2.25, with high directivity D=0.75 and low reflection coefficient RC<1%. The maximum power density is 41 MW / m^2, which is acceptable for HL-3 LHCD system. The whole antenna body is separated to 8 modules, all made of stainless steel. The RF characteristic of the antenna is tested via special designed measurement components. The test result shows that the reflection coefficient, transmission characteristic and the phase shift of the grills match the design, indicating the antenna is well manufactured.

FIG. 4. Photo of the FAM launcher in HL-3. A gas puffing system with tree poloidal injections are located at the left of the launcher mouth (as viewed from the plasma). A set of Langmuir probes is located to the right.

3. LHCD EXPERIMENT ON HL-3

The LHCD system was demonstrated in 2023 for the first time. The coupled power has reached 1 MW with coupling coefficient 95% since 2025, where 490kW maximum power was delivered in a WR284 standard WG transmission line. The loss of the transmission lines are quite high, 20% - 40% efficiency of the four lines, respectively. The coupling optimization experiments were also carried out. Gas injection next to the antenna was applied not only for density control, but also for the coupling optimization, which is effective in the experiments. Full non-inductive current drive phenomenon was also obtained in the experiments. 300 kA plasma current was driven by 800 kW coupled LH power.

3.1. Current drive experiment

Full non-inductive current drive phenomenon was obtained in the experiments, which is shown as FIG. 5. The loop voltage decreased during the LHW injection and became zero V. At the same time, the CS coil current keeps constant, showing zero gradient. Those phenomenon indicates the full non-inductive current drive happening in shot 6697. In other words, the plasma current was driven totally by LHCD. The plasma current is 300 kA. The signal drew in purple line shows the forward power nearby the antenna, reflected power subtracted. So it could be considered as the coupled power, which is about 800 kW. The density is about 1.3×10^{19} m^{-3}. In the mean while, the stored energy increased during LHW power injection, showing heating effect in a way. According to the formula $\eta_{CD}=n_e \cdot R \cdot I_{CD} / P_{LH}$, the CD efficiency was estimated as 0.87×10^{19} $AW^{-1}m^{-2}$.

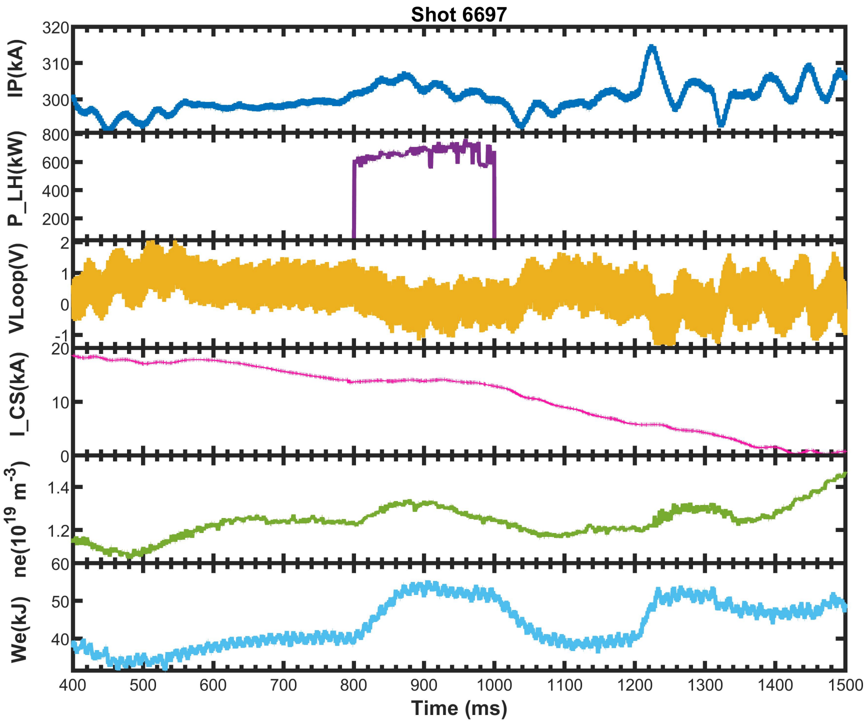

FIG. 5. Full non-inductive current drive shot. From top to bottom are plasma current (IP in kA), coupled LHW power (P_LH in kW) , loop voltage (VLoop in V), CS coil current (I_CS in kA), electron density (ne in 10^{19} m^{-3}) and stored energy (We in kJ), respectively.

3.2. High power coupling

The HL-3 LHCD system is quite new, which needs a long term for practice. As a basic solution, coupling optimization was carried out, where gas puffing was used frequently. As there is another gas puffing port nearby the LH antenna window, settled in No. 16 while LH antenna located on No. 15 window, the gas puffing system on the antenna was not applied. The adjacent gas puffing system shows benefits to the coupling.

As shown in FIG. 6 below, the gas puffing runs during the LH injection. The gas was ionized and generated lights in the right side of the visible spectrum Charge-Coupled Device (CCD) figure, where the gas puffing port located. After LHW injection, since the gas puffing was cancelled, the ionization light disappeared.

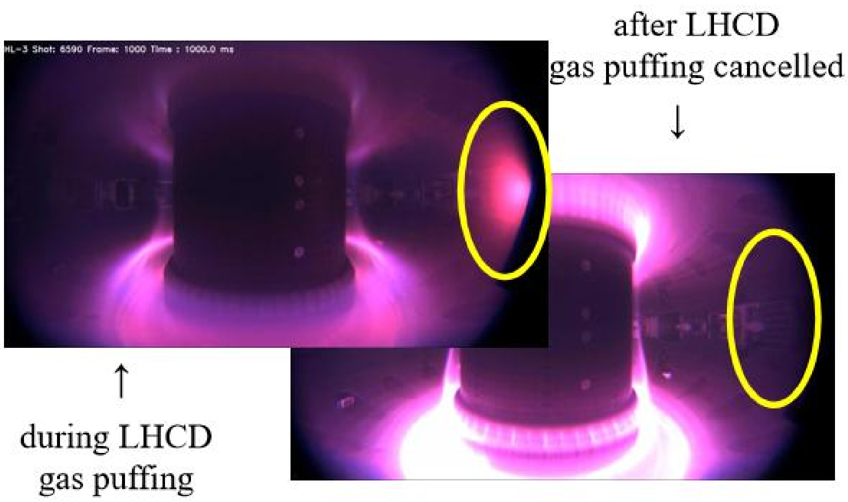

FIG. 6. Visible spectrum CCD figure of shot 6590.

In this way, the system was well practiced and the coupled power increased year after year. In shot 12929 (2025 experimental campaign), the coupled LHW power reached 1 MW [9] with 5% Reflection Coefficient (RC) in the case of 0.5 MA plasma current. As shown in FIG. 7, the loop voltage decreased while the storage energy increased during the LHW injection. The density also increased probably because of the ionization enhancing nearby the antenna according to the high power injection.

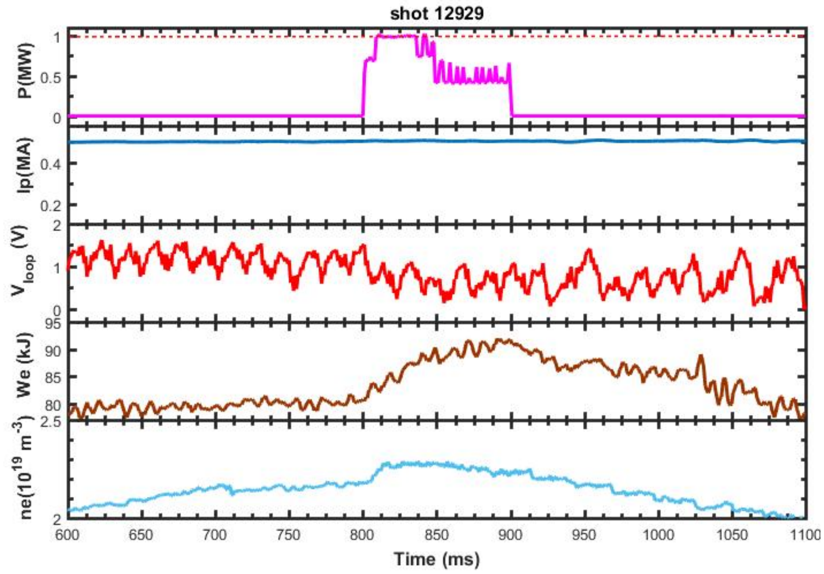

FIG. 7. 1 MW LHW power coupled into the HL-3 plasma in shot 12929. From top to bottom are coupled LHW power (P in kW), plasma current (I_P in kA), loop voltage (V_{Loop} in V), stored energy (We in kJ) and electron density (ne in 10^{19} m^{-3}), respectively.

3.3. H-mode experiment

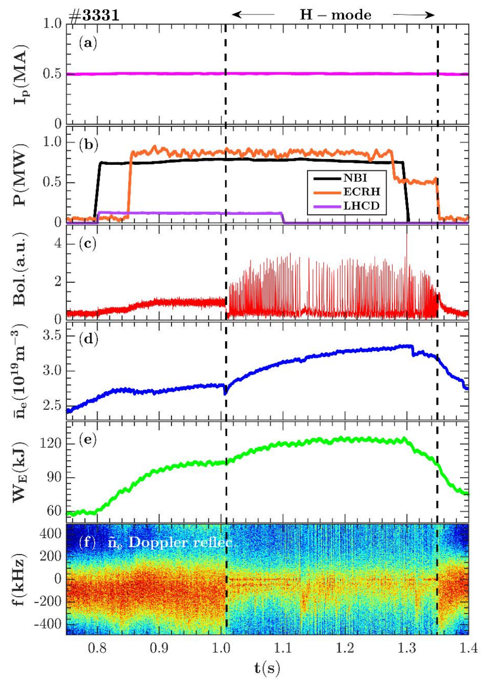

FIG. 8. The first H-mode operation of HL-3 in 2023. From top to bottom are plasma current (I_P in MA), heating power (P in MW) where NBI in black, ECRH in orange and LHCD in purple, bolometer signal (a.u.), line

averaged electron density (n_e in 10^{19} m^{-3}), stored energy (W_E in kJ) and the spectrum of the Doppler reflectometry (f in kHz), respectively.

As FIG. 8 shows, the first H-mode of HL-3 was obtained in heating duration, including NBI, ECRH and LHCD. The ELM behaviour changed when LHCD was shut down. The frequency of the burst decreased without LHW power.

4. SYSTEM UPGRADE SITUATION AND PLAN

After the campaign of 2025, HL-3 goes into the upgrading duration for deuterium-tritium operation. The LHCD system is also on upgrading from 2 MW to 4 MW. The new 2 MW system will be developed and the original system will be modified to match the requirement of deuterium-tritium operation. There will be 8 klystron in the system, each of which can output 500 kW power in two arms. For the new system, the klystron will be supplied by the domestic supplier but with the similar parameter. So the power will be recombined by power combiner and divided at the antenna side, making 8 transmission lines. There will be two antennas launching power via No.11 and No.15 port on the vacuum chamber of HL-3. Each antenna is served by 4 klystrons.

To improve the safety of the system, two ceramic windows will be installed on one transmission WG, with 0.3 MPa pressure nitrogen gas between them, as same as the transmission lines. To decrease the transmission loss in the long transmission lines, which would exceed 60 m after upgradation, higher harmonic mode will be used instead of base mode. Circle WG transmitting TE01 mode, which could decrease the edge current loss in the transmission line, will be installed in the system. The mode converter for TE11-TE01 and TE01 bend have been developed. High power test has been carried out, shown as FIG. 9, in which more than 450 kW power capacity was obtained, indicating the components were well designed and manufactured. Now more mode converters and TE01 bends are on manufacturing and will be installed in the new system. Two FAM concept antennas were designed for the new system while the original one manufactured 10 years age will retire. The support structure of new antennas are improved, hydraulic technology used for the antenna moving in radial direction. And also more safety design was considered to avoid damage in the accident situation, including mechanical locking and electronic locking.

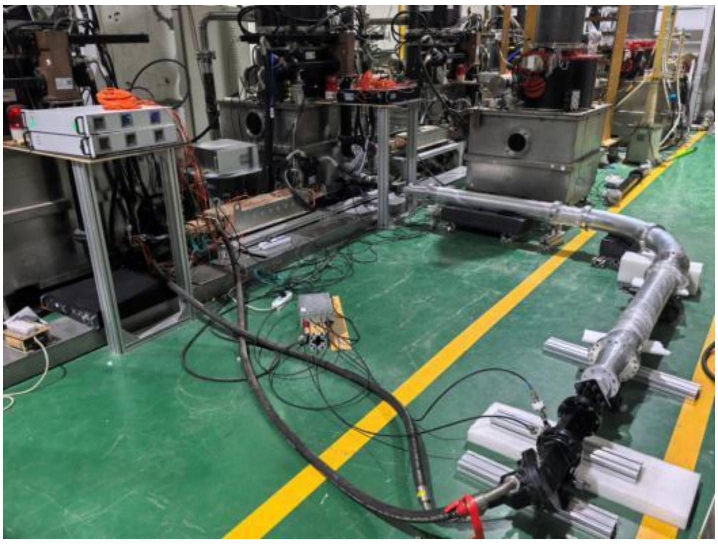

FIG. 9. Photo of the mode converter high power test bed. The high power was generated from the klystron and transmitted through a circulator, a directional coupler, the rectangle-circle converter, the mode converter, another mode converter, bend, another mode converter, another rectangle-circle converter, another directional coupler and a dummy load, respectively. The power reached 450kW in the test experiment, which is limited by the non-conditioned new excitation source. It can be inferred that the mode converter can bear more power.

The upgradation is planned to be finished in 2026. And then goes into the commissioning period.

5. CONCLUSION

A 2 MW / 3.7 GHz / 3 s LHCD system was developed on HL-3 tokamak, demonstrated well in the recent experiments. The coupled power reaches 1 MW and helped to obtain H-mode. Also non-inductive current drive phenomenon was obtained by LHCD. The system is now on upgrading and will reinstalled in 2026 for deuterium-tritium operation preparation.

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