Coupling optimization experiment on HL-2A based on Passive-Active Multijunction antenna for 3.7GHz Lower Hybrid system

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System Introduction. A new Lower Hybrid Wave (LHW) system (3.7GHz/2MW/2s) has been built on HL-2A tokamak. A Passive-Active-Multijunction (PAM) concept antenna [1], [2] was designed and built, fed by 500kW × 4 TH2103A Klystrons, delivering ITER-relevant power density, i.e. 25MW/m^2 at f = 3.7GHz [3],[4]. The antenna is designed to launch a peak parallel refractive index of $N_{||}$=2.75 with a low theoretical Reflection Coefficient (RC), i.e. less than 1% [5], [6]. A specific gas puffing system for improving the antenna coupling and a set of Langmuir probes for antenna mouth density measurements are separately located on one side of the antenna each. An auxiliary vacuum system is installed at the rear of the antenna to improve the pumping efficiency. Vacuum leak tests and low power microwave scattering parameter measurements were done before the PAM antenna was installed on HL-2A, allowing the antenna to be conditioned at RF power of 100kW/100ms before starting plasma operation.

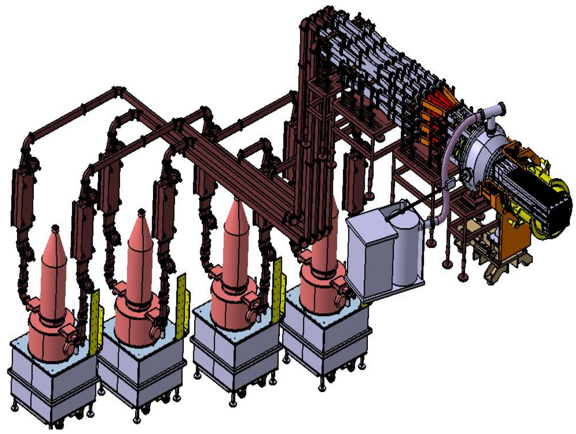

Fig. 1: New LHW system（3.7GHz/2MW/2s）of HL-2A. 500kW × 4 TH2103A Klystrons are located on the ground floor and the antenna is on the first floor, with an auxiliary vacuum system beside it.

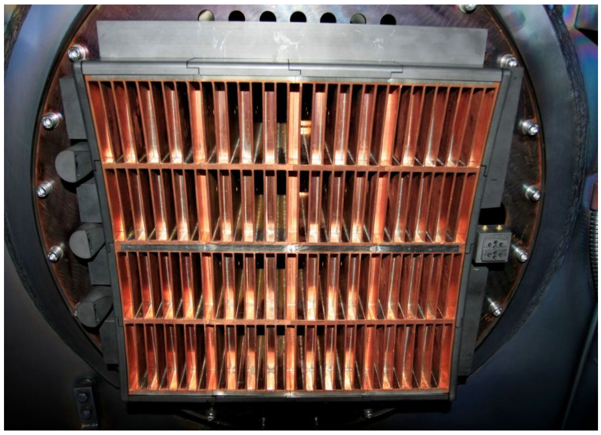

Fig. 2: PAM launcher was developed and installed, facing to the plasma of HL-2A. A set of eight Langmuir probes is located on the right side, while gas puffing system is on the left side.

Commissioning. Commissioning work for the transmission line and the PAM antenna was carried out after the klystrons had been operated on test bed at full output power and duration.

Initially, the antenna was set about 3cm behind the limiter to guarantee safe operation, since the antenna had not been baked before installation. The commissioning work lasted about one month at RF power of 100kW/100ms. After the commissioning, the coupling was found to be improved, i.e. power reflection coefficient (RC) of ~10-30%, compared to almost 100% before the commissioning. The coupling optimization was then carried out.

Coupling optimization experiments. Coupling optimization experiments were carried out in both limiter and divertor configuration on HL-2A with the PAM antenna. From the calculated results by the ALOHA code (Fig. 3) it is found that optimum coupling, i.e. lowest power reflection coefficient (RC), is obtained for $n_e \sim 5\times10^{17}m^{-3}$. The RC revolution with density is shown in Fig. 3, which also shows that RC increases strongly when approaching the cut-off density ($n_{co} = 1.7\times10^{17}m^{-3}$ for f = 3.7 GHz). The edge density at the antenna mouth affects LH coupling much according to the calculation results, which was also obtained during the optimization experiments, as shown in Fig. 4.

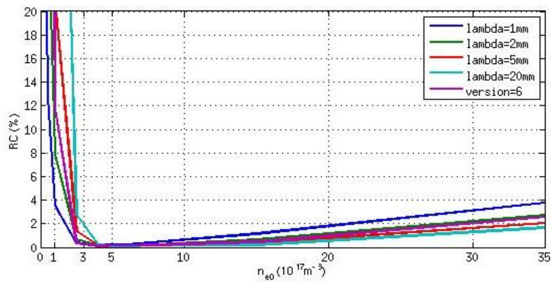

Fig. 3: Reflection coefficient on the PAM launcher versus electron density at the launcher mouth from ALOHA code results.

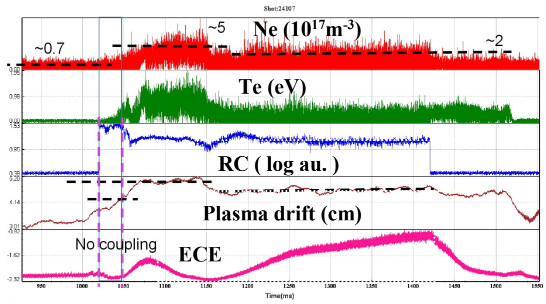

Fig. 4: RC revolution during electron density changes at the launcher mouth. The density is measured by Langmuir probes. (Note that RC is displayed in log scale).

The experimental results show that if the density at the launcher mouth is less than $1\times10^{17}m^{-3}$, i.e. below the cut-off density, the wave is not coupled. If the density is around $5\times10^{17}m^{-3}$, the RC is low, in accordance with ALOHA calculations. Good coupling was obtained both in limiter and divertor configuration in the optimization experiments with the help of different methods, such as gas puffing, launcher position change, plasma position control and plasma density change. The injected LH power reached 500kW. The experiments were performed in the optimized parameter range of average RC lower than 10% with 400ms duration, which makes it possible to carry out further LH physics experiments on HL-2A with the PAM.

When the antenna is not very close to the plasma, the density at the antenna mouth is often lower than the cut-off density n_{co}, and the coupling is very weak. In these cases a gas puffing in front of the antenna mouth is always needed for improving the LH coupling. Due to the non-uniformity of the gas puffing at the antenna mouth, the RC distribution in different grills was not uniform either. The coupling is worse at the top grills than that at the bottom ones.

This asymmetry was more obvious in the divertor configuration, due to the single null with lower X-point of HL-2A. Generally it has been found that more the gas puffing, better the coupling. Parameters controlling the gap between the antenna mouth and the plasma include the antenna position, the limiter position and the plasma drift in horizontal direction in the divertor configuration. The gap was selected between 1cm and 10cm during the optimization experiments. The coupling is better with smaller gap as expected shown in Fig. 5. But sometimes smaller gap caused plasma disruptions, since the plasma touched the wall in the divertor. The plasma shape control was therefore also very important for the optimization of the coupling. Another interesting parameter affecting coupling was plasma drift in vertical direction, shown in Fig. 6. When the plasma is slightly moved upwards, the value of RC at the bottom grill of the antenna is reduced from 19% to 12%, while that at the top grill is reduced from 99% to 58%.

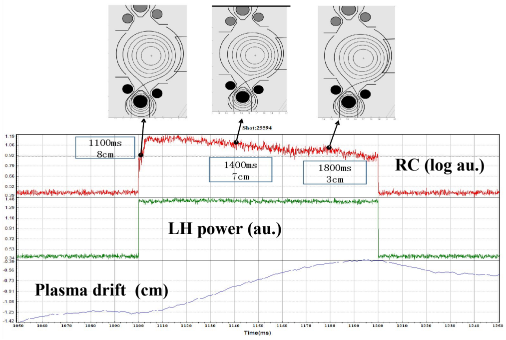

Fig. 5: Gap affects coupling in divertor configuration.

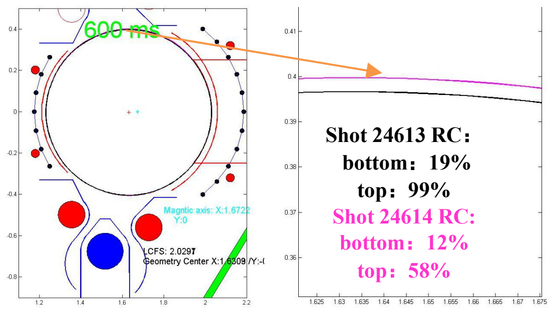

Fig. 6: Plasma drift in vertical direction affects coupling in limiter configuration.

Plasma behaviour. Lower Hybrid Current Drive（LHCD）and Heating (LHH) effects have been observed in the coupling experiments as shown in Fig.7. Indeed, during the LHW phase, the loop voltage is clearly decreased due to the non-inductive current driven by suprathermal electrons generated by LHCD, while the stored energy is increased showing the LHW heating effect. However the LHW power is not high enough to give fully non-inductive current drive in the present LHCD experiments. Fig.8 shows the temperature profile measured by ECE diagnostic at different time. The ECE signals at t=1300ms show clearly that the temperature profile is strongly affected by suprathermal electrons generated by LHCD, especially the edge channels. ECE signals, extremely sensitive to the suprathermal electron population in the plasma, can be considered as good indications for the suprathermal electrons.

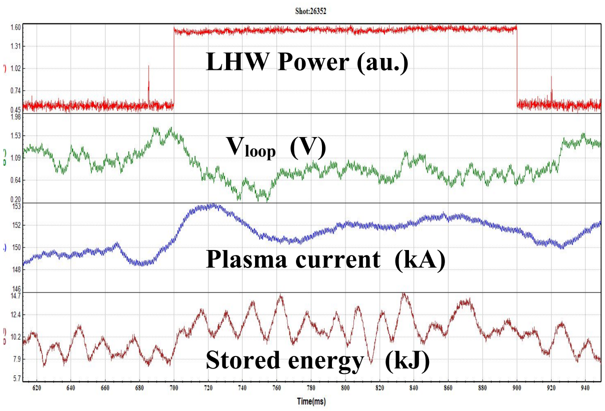

Fig. 7: LHCD & LHH effects observed during LHW injection in shot No. 26352. The loop voltage dropped due to LHCD and the stored energy increased due to LHH.

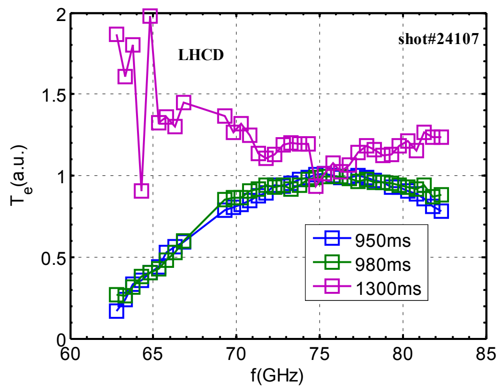

Fig. 8: Temperature profile measured by ECE diagnostic at different time: 950ms, 980ms in the phase without LHCD, and 1300ms with LHCD, The profile illustrates the effect on the temperature of suprathermal electrons generated by LHCD.

Summary and Perspective. A new 3.7GHz LHW system was built and exploited on the HL-2A tokamak. The PAM concept antenna was installed and commissioned. Coupling optimization experiments of the LHW system were carried out, in which the coupled LH power reached 500kW/400ms. A power reflection coefficient (RC) less than 10% was obtained in both limiter and divertor configuration. The key parameters affecting LH coupling were also studied. Effects on the plasma, such as LHCD, LHH and suprathermal electrons were observed in those experiments. These first promising experimental results will allow performing further physics experiments with the PAM antenna on HL-2A. In the near future, the transmission line efficiency would be increased by improving the flexible waveguides. And the gas puffing system would also be modified to make the gas quantity more controllable. With those hardware improvements, the LHW system will be able to deliver higher power in longer duration (2MW/2s), which would be high enough to give fully non-inductive current drive, or to trigger H-mode with LH alone.

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