IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received April 19, 2018, accepted June 12, 2018, date of publication July 4, 2018, date of current version July 25, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2851982

Power Modulation System and Experiments of Lower Hybrid Wave on EAST

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This work was supported in part by the National key research and development program under Grant 2016YFA0400602 and Grant 2016YFA0400603, and in part by the National Natural Science Foundation of China under Grant 11675212 and Grant 11775259.

ABSTRACT To satisfy various requirements of different physics experiments, a new power modulation method of the lower hybrid wave (LHW) has been developed in Experimental Advanced Superconducting Tokamak (EAST), including the development of a control source combining software and hardware. Such modulation system is realized by the main positive-intrinsic-negative diode switch located at the oscillator. The LHW modulation system has been installed and tested, demonstrating that the modulation parameters can be controlled flexibly. The maximal modulation frequency is about 10 kHz, which is limited by the hardware circuit speed. The system has been successfully used to study the influence of LHW on the performances of plasma. Under the modulation of LHW, strong mitigation of edge-localized modes (ELMs) has been observed, and ELM pace-making technique has been demonstrated. Further experimental studies with the modulation system will be continued in EAST.

INDEX TERMS LHCD, EAST, power modulation, ELM.

I. INTRODUCTION

Experimental Advanced Superconducting Tokamak (EAST) [1,2] is the first fully superconducting tokamak with major radius R $\sim$ 1.8 m, minor radius a $\sim$ 0.45 m, plasma current $I_p < 1.0$ MA [3], toroidal field $B_T < 3.5$ T, and its target is to demonstrate high performance and long pulse operation up to 1000 s. The lower hybrid current drive (LHCD) has been an extremely important method to approach the goal on EAST.

LHCD has been playing an indispensable role in current drive [4]–[7] and current profile control [8], [9] after Fisch presented the theoretical proposal [10]. Various physics experiments require different lower hybrid wave (LHW) power modes. Long pulse of 411s discharge ($I_p \approx 0.28$MA, $n_e \approx 1.2 \times 10^{19}$/m3, $T_e \approx 1.8$keV, $P_{LHW} = 1.2$MW) with LHW power feedback control by the flux loop in 2012 has been obtained in EAST [11]. Besides, LHW power modulation is a powerful tool for power deposition and current drive efficiency study [12], [13]. Modulated LHW power was also used to depress MHD on HT-7 tokamak [14], [15] and to mitigate edge-localized modes (ELMs) [11] on EAST.

In some cases, LHCD power modulation with a high frequency up to 10 kHz will be required. LHW power modulation can be realized via the exciter or the high voltage power supply (HVPS) of klystrons. Considering the difficulty to obtain high frequency modulation of HVPS, the power modulation is implemented by the exciter in EAST. The power modulation system and experiments of LHW will be introduced in this paper.

II. LHW POWER MODULATION

A. LHCD SYSTEMS ON EAST

In order to achieve steady state operation with high plasma parameters, two LHCD systems have been built and commissioned early or late on EAST. The first 2.45 GHz LHCD system was built in 2008 and then updated from 2MW/CW [16] to 4MW/CW in 2012. The second one working at the frequency of 4.6 GHz with the power of 6MW/CW was constructed in 2013 and put into use on EAST in 2014 [17]. The parameters of two LHCD systems are showed in the following table I.

B. WAVE EXCITER OF KLYSTRON

The LHW wave exciter system is used to feed all klystrons with low power microwave signal while providing interface

TABLE 1. Parameters of the two LHCD systems on EAST.

Parameters	LHW1	LHW2
Frequency	2.45GHz	4.6GHz
Designed/Projected Power	4MW/CW	6MW/CW
Quantity of klystron and its output power（kW）	20×200	24×250
Klystron beam voltage	45kV	45kV
Klystron beam current	11A	12.1A
Klystron efficiency	＞40%	＞45%
Range of $N_{//peak}$	2.09~2.58	1.8~2.26
Range of the displacement of the antenna	±150mm	±50mm
Obtained maximum injected power and longest duration	2.8MW/6s 1.2MW/410s	3.5MW/2s 1.4MW/101s

circuits for the power and phase control, high reflection, arc and over-current protection as well as safeguard in other emergent cases. FIGURE 1 shows the wave exciter of 4.6 GHz LHCD system, and the structure of 2.45GHz LHCD wave exciter is almost identical to it except number of the chains.

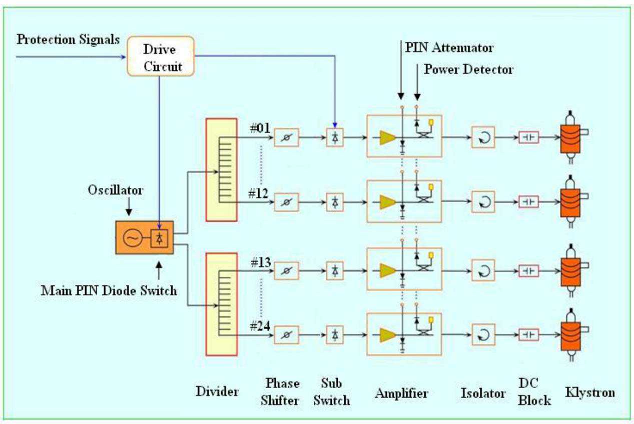

FIGURE 1. The wave exciter of the 4.6GHz /6MW LHCD system.

There are one oscillator, one main positive-intrinsic-negative (PIN) diode switch, two 1:12 power dividers, and 24 identical wave drive chains in the wave exciter. Each of the chains consists of a digital phase shifter, a sub PIN diode switch, an amplifier with a voltage controlled PIN diode attenuator and a detector, an isolator, etc. The main PIN diode switch integrated in the master oscillator is used for protection of plasma interlock and the sub PIN diode switch on each chain of the exciter is installed for high voltage standing wave ratio (VSWR) and arc protection. The PIN diode attenuators in the amplifiers are used for power control with a dynamic range of 20 dB. All the digital phase shifters are dedicated to wave phase control aiming to change power spectrum with a phase adjustment range of 360° and a control step of 5.6°. Every chain eventually connects to the corresponding klystron's input port.

C. REALIZATION OF NEW LHW POWER MODULATION

LHW power modulation was implemented through switching on or off the klystrons' input power by the sub PIN diode switches on the exciter system before 2012 on EAST. This method integrated in the VSWR protection system based on software process is subject to signal distortion under high modulation frequency easily leading to power discontinuity and power spectrum shifting. Therefore, it is necessary to develop a new LH power modulation regime. In order to obtain high performance modulation, the main PIN diode switch is adopted to realize the new LHW modulation regime on EAST.

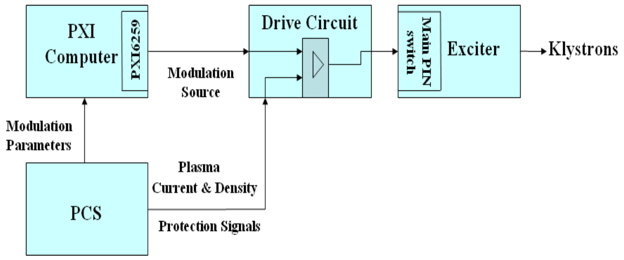

FIGURE 2. LHW Power Modulation system.

The new modulation method is independent of the VSWR protection system by controlling the main PIN diode switch (see FIGURE 1), which was only dedicated to plasma interlock before 2012. This new modulation method is easier to realize and more robust than the former one. As shown in FIGURE 2, the new LHW power modulation system consists of a PCI eXtensions for Instrumentation (PXI) computer equipped with a digital output (DO) card PXI-6259 of National Instruments., Ltd (NI), the main PIN diode switch and a switch drive circuit. The plasma control system (PCS) sends modulation parameters to the PXI computer through control Ethernet including the modulation frequency, duty ratio, start and stop time of modulation. According to the modulation parameters, the modulation program running on the PXI computer creates a digital pulse output task on the PXI-6259 and then waits for a trigger signal from PCS. Once PCS sends the trigger signal to the PXI computer, the modulation program starts the previously created task instantly and the modulation signal, a voltage square wave sequence with specified frequency, duty ratio as well as start and stop time, will be generated by the PXI-6259. The modulation signal is applied on the main diode switch through the drive circuit to turn on and off the main diode switch periodically, thus all klystrons' output power, namely the LH power is modulated.

The maximal modulation frequency is constrained by the main PIN diode switch and the wave detectors in LHCD system. Due to the charge storage effect, PIN diode has a characteristic called switching time T_{switch}. T_{switch} is spent by PIN diode to switch on or off itself when bias voltage is applied on or canceled respectively. Consequently the frequency of the modulation signal must be limited not greater than $1/T_{switch}$. Test of the switching time of the main PIN

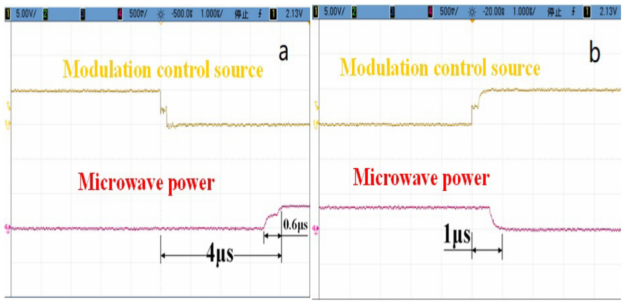

FIGURE 3. The main PIN diode switch time test result. (a) switch-on time, (b) switch-off time.

diode is performed and the result is presented in FIGURE 3. FIGURE 3 (a) and (b) show the switch-on and switch-off time of the main PIN diode separately. The yellow waveform represents the modulation signal generated by the PXI-6259 and the red one is the output microwave power signals detected by the detectors without capacitance. The switch on and off time are about 4μs and 1μs respectively, and the power ramp-up time is about 0.6μs so that $1/T_{switch} \leqslant 10^6$*(1/5.6)Hz.

As the LHCD system field is close to the ECRH system and EAST hall, electromagnetic noises brought by EAST discharge will produce negative influence on the detection voltage signal of the wave detectors for LHW power measurement. In order to filter the spike noises in LHCD field, each wave detector used in LHCD is equipped with a filter capacitance that prolongs the step response time of the wave detector. The difference between response times of wave detectors with and without the capacitance to modulation signals is also checked at different modulation frequencies as shown in FIGURE 4. The yellow trace is the modulation signal from the PXI-6259; the green one is measured microwave power signal detected by a detector with a filter capacitance, and the blue one is the actual microwave power signal detected by a detector without the filter capacitance. The actual output microwave (blue) is modulated well at 10 kHz but not so well with false duty ratio at 100 kHz. For the measured microwave power signal (green), there is a slight distortion at 10 kHz and becomes seriously at 100 kHz. The anamorphic signals are due to longer response time caused by the filter capacitance. From above it can be concluded that the

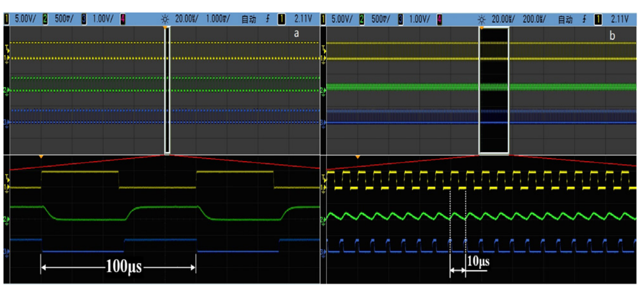

FIGURE 4. Power Modulation frequency test. (a) frequency at 10 kHz, (b) frequency at 100 kHz.

maximum modulation frequency is limited to min$\{1/T_{switch}, 10\text{kHz}\} = 10$ kHz.

Up to now, the maximum frequency at 10 kHz of LHW modulation has satisfied various requirements of different experiments in EAST. The new modulation method has been deployed on 2.45 GHz and 4.6 GHz LHCD systems with parameters as follows: frequency at 0 $\sim$ 10 kHz, duty ratio at 0 $\sim$ 1 and flexible control of start and end time of the modulation. FIGURE 5 shows the experiment of LHW power is switched on and off at the frequency of 10 kHz on 2.45 GHz LHCD system.

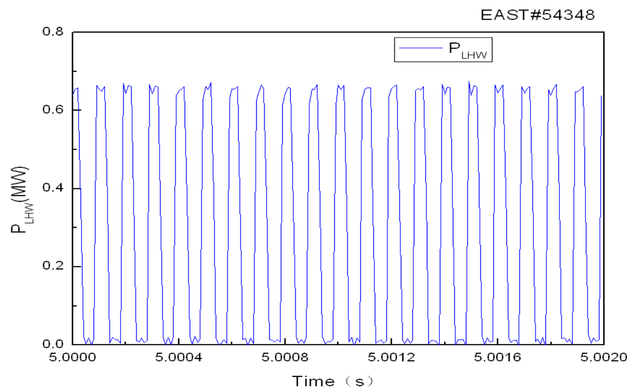

FIGURE 5. 2.45 GHz LHW power modulation at 10 kHz.

III. EXPERIMENTS OF LHW POWER MODULATION

ELM is a challenging issue to be resolved for tokamaks and future DEMO and fusion plants, and numbers of strategies and methods has been developed for ELM suppress or control [18]. LHCD is found effective for ELM mitigation for the first time on EAST [19]. The influence of LHW on the characteristics of ELMs has been further studied through the LHW power modulation in H-mode plasma [11]. Fast switching-on LHCD (at 10 Hz with 50% duty cycle) appears to trigger small amplitude, high frequency ELMs, or even completely suppress ELMs as shown in FIGURE 6 for an ICRH dominated H-mode plasmas.

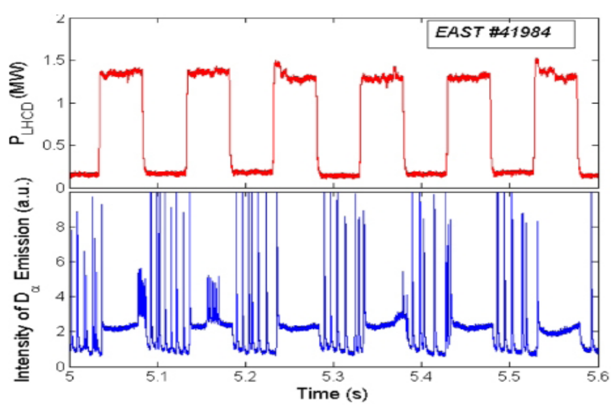

FIGURE 6. The effect of modulating the LCHD power on ELMs indicated by the D_α emission measured from the outer divertor.

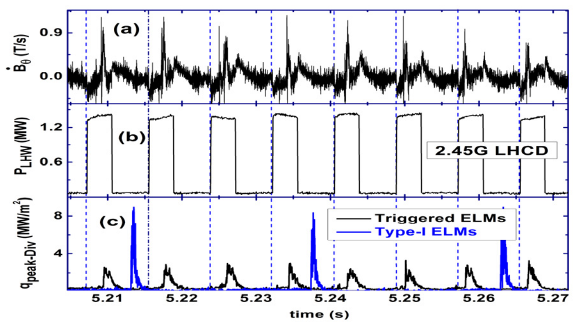

FIGURE 7. ELM pace-making by LHCD power modulation at 120 Hz. Time traces of (a) poloidal magnetic perturbation on the low-field side, (b) 2.45GHz LHCD power, (c) diverter peak heat fluxes for triggered ELMs (black) and natural type-I ELMs (blue).

Also a new ELM pace-making technique by LHCD power modulation has been demonstrated, for the first time, on EAST [20]. The achievable pace-making frequency is up to 120 Hz, appearing to be limited only by the pedestal recovery time. As shown in FIGURE 7 (c), the peak heat flux on the divertor targets is reduced by a factor of ~3 (from ~9 to ~3 MW/m^2) and the ELM frequency increased by a factor of ~3 with respect to the natural type-I ELMs. The product of ELM frequency and divertor peak heat flux keeps nearly constant, $f_{ELM} \cdot q_{peak-Div} \sim 360$ Hz $\cdot$ MW/m^2. In addition, the stored energy reductions of the triggered ELMs are too small to be resolved by the diamagnetic measurement.

IV. CONCLUSION

A new power modulation method of lower hybrid wave (LHW) has been developed to satisfy the requirements of all the experiments in EAST tokamak. The new LHW power modulation method supports modulation frequency up to 10 kHz with flexible modulation parameters. The new system has been deployed on both 2.45GHz and 4.6GHz LHCD systems on EAST and applied in ELM pace-making and mitigation experiments, and is found effective to suppress the plasma ELM instabilities, which is beneficial to the plasma stability.

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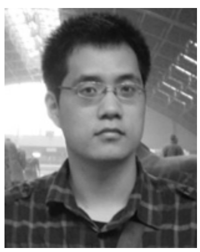

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