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Power measurement system of ECRH on HL-2A

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Abstract. Electron Cyclotron Resonance Heating (ECRH) is one of the main auxiliary heating systems for HL-2A tokamak. The ECRH system with total output power 5MW has been equipped on HL-2A which include 6 sets of 0.5MW/1.0s at a frequency of 68GHz and 2 sets of 1MW/3s at a frequency of 140GHz. The power is one of important parameters in ECRH system. In this paper, the method for measuring the power of ECRH system on HL-2A is introduced which include calorimetric techniques and directional coupler. Calorimetric techniques is an existing method, which is used successfully in ECRH commissioning and experiment, and the transmission efficiency of ECRH system is achieved by measuring the absorbed microwave power in the Match Optical Unit (MOU), gyrotron output window and tours window of the EC system use this method. Now base on the theory of electromagnetic coupling through apertures, directional couplers are being designed, which is a new way for us.

1 Introduction

As one of the main heating system of many fusion experimental devices, including ITER, ECRH has been widely applied on plasma heating, non-inductive current drive, plasma start-up, current profile control and MHD stabilization [1, 2]. In ECRH system, the high power millimetre wave radiated from the gyrotron and transmitted to an EC launcher in HE_{11} mode through transmission line where oversized corrugated waveguide are used, finally injected into plasma by the EC launcher.

At present, the ECRH system on HL-2A has equipped with six 0.5MW gyrotrons at 68GHz and two 1MW gyrotrons at 140GHz, the total output power is 5MW. As shown in Table1:

Table 1. Parameters in ECRH system on HL-2A

Output power	Frequency	Pulse	Transmission line
3MW(6*0.5MW)	68GHz	1s(1.5s)	F80mm,non-evacuated
2MW(2*1MW)	140GHz	3s	F63.5mm, evacuated(10-2Pa)

The highest output power of 2.5MW has been attained with the six gyrotrons and the H-mode discharge has been realized with the 68GHz ECRH system and a 1MW NBI system. The new 140GHz/2MW/3s systems are planned to inject the second harmonic waves in X-mode to do higher power plasma heating and current drive in higher plasma density.

The power is one of the important parameters in ECRH system. Calorimetric methods has been used for measuring power in ECRH commissioning and experiment on HL-2A. Use this method, the microwave energy is converted into water energy which can be calculated by measuring water temperature increment. The principle and measurement results of calorimetric methods are introduced in this paper.

Because the time delays of water temperature acquisition, the power information is not in real time. Directional couplers are being designed which can measure the power in real time and also can be used to monitor the gyrotron oscillation status.

2 Calorimetric methods

In calorimetric methods, the power is measured by detecting increment of the temperature difference between inlet and outlet of cooling water flowing through components in transmission line with a calorimetric system. This method can be used in any component which has cooling water.

2.1 Principle

On condition that the microwave energy converted into water energy completely, the energy balance is expressed by following equations [3]:

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$$P_w \cdot D_w = W \tag{1}$$

Here, P_w is the power of microwave, D_w is the duration time, W is the energy of cooling water, and the water flow is constant.

According to the thermal equation of energy, we can obtain W by two temperature sensor which installed at the cooling water inlet and outlet of the component separately:

$$W = JQ = JCm\left(T_2 - T_1\right) \tag{2}$$

Here J=4.1868J·cal^{-1} which is called thermal energy yield, m is quality of water, T_2 and T_1 are the temperature measured by temperature sensors.

For the water with water flow F, the time from t_1 to t_2, the total thermal energy is express as:

$$W = JCF\int_{t1}^{t2} T\left(t\right)dt \tag{3}$$

Where $T\left(t\right) = T_2\left(t\right) - T_1\left(t\right)$. The flowing equations can be obtained by Eqs.(1) and Eqs.(2):

$$P_w D_w = JCF\int_{t_1}^{t_2} T\left(t\right)dt = JFCS_w \tag{4}$$

Here, $S_w = \int_{t_1}^{t_2} T\left(t\right)dt$. The J , F , and C are constant during this measurement process. D_w is the pulse duration of the microwave, which is measured by a detector. So the power of the microwave P_w is given by the Eqs. (4).

The typical curves of the temperature increment $V_{\Delta T}$ and the integral of the temperature increment S are:

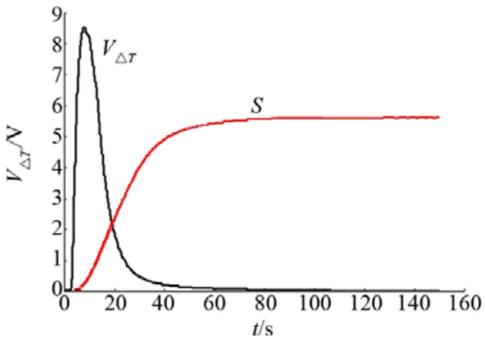

Figure 1. The typical curves of the temperature increment

It can be seen from the Fig.1, more than 100s is taken to reach zero of the cooling water temperature.

In practice, a substitution method is applied in the measurement in order to ignore the exact values of water flow. The cooling water is heated by an electric power with known power P_k and pulse duration D_k , through the electrical heater installed in the calorimeter. We also can obtain the temperature increment and integral in this process which called calibration.

$$P_w = k\frac{S_w}{D_w} \tag{5}$$

Here, $k = P_k D_k / S_k$ is calibration coefficient. The calibration is done before the ECRH system is operated.

2.2 Components of the calorimetric methods system

Power measuring system consists of calorimeter, RTD (integration of temperature increment signal), electronic unit and timing power supply, and measured data are recorded and processed by a data acquisition and process system.

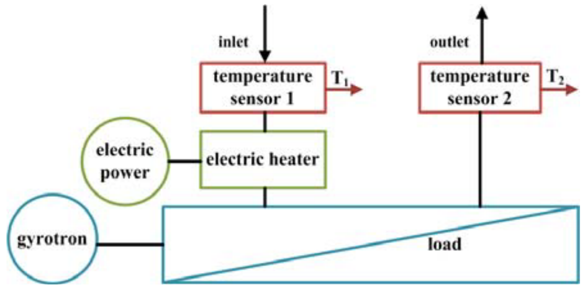

Figure 2. Schematic diagram of calorimetric unit

The temperature is detected by two temperature sensors installed in the calorimeter and the temperature increment measured by a measuring instrument which is designed base on a multistage differential op-amp circuit. The temperature sensor is a negative temperature coefficient resistance (NTC). The typical curve of the NTC is shown in Fig.3:

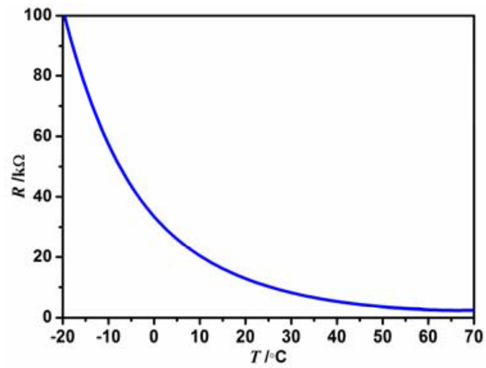

Figure 3. The typical curves of NTC

The calorimeters were installed on Match Optical Unit (MOU) and the window near the EC launcher separately in each ECRH system. And the directional couplers are being designed which will be installed on one of the miter bends. As shown in Fig.4:

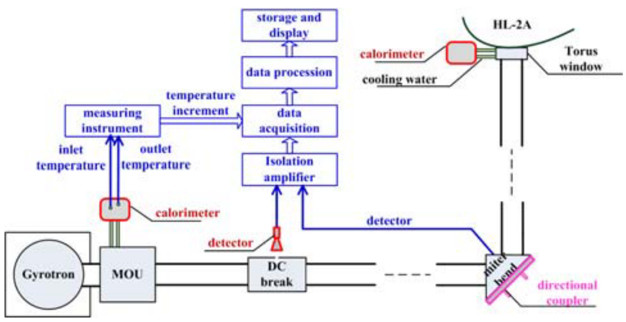

Figure 4. The location schematic diagram of calorimeters installed

To measure the pulse duration of the microwave, a detector is installed on DC break which has a gap in non-evacuated system. But there is no gap on the DC break in evacuated system, so we put the detector on the MOU which has a small window for detector. The signal measured by the detector is shown in Fig.5:

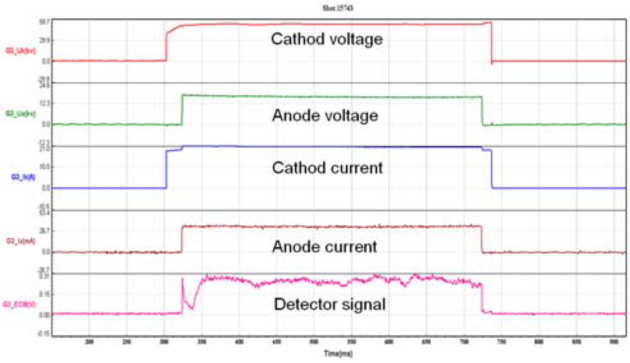

Figure 5. Power supply and detector signals

In Fig.5, the last one is the detector signal which is a diode detector and this signal is a voltage. The pulse duration measured by detector is always equal to the duration time of the anode under normal conditions.

2.3 Measurement result

In ECRH system, the output power of gyrotron is calculated always through MOU. The power absorbed by MOU is spurious mode power. In order to obtain the power of useful mode, the percentage of the spurious mode must be got in commissioning.

A dummy load (DL) is installed in commissioning after MOU, which is a full absorption water load and absorbs the useful mode [4]. To measure the power absorbed by dummy load, the calorimetric methods is applied. The photo of dummy load and its reflector are shown in Fig.6 and Fig.7.

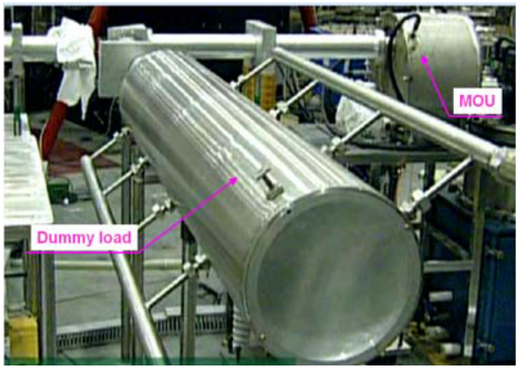

Figure 6. Dummy load

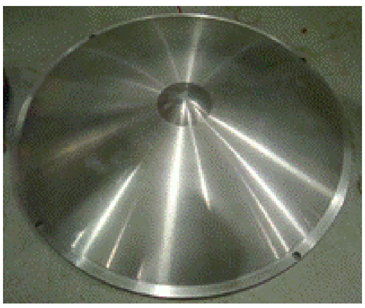

Figure 7. Underside of dummy load

The percent of spurious mode power absorbed by MOU is obtained by measuring the power at dummy load and MOU. In commissioning, 30 shots data are shown in Fig.8, the percentage of spurious mode power absorbed by MOU is about 11% in 68GHz system and it is about 5% in 140GHz system.

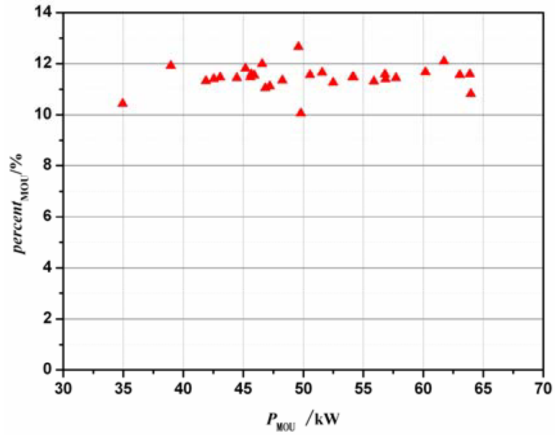

Figure 8. The percentage of the spurious mode power absorbed by MOU in 68GHz system.

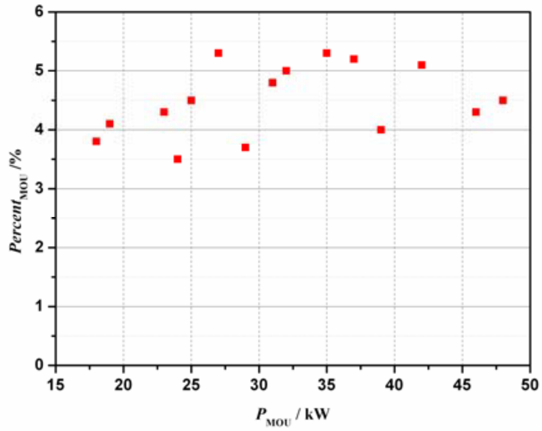

Figure 9. The percentage of the spurious mode power absorbed by MOU in 140GHz system.

A window is installed on the output port of the gyrotron and also on the end of the transmission line. For 68GHz system, the window is BN and CVD for 140GHz system. We know that the window should be cooled because the temperature of the window is rising when the microwave through it.

According to the difference of the gyrotron and window, there are three methods to solve the cooling problem, which are distributed, liquid-edge-cooled, gas-surface-cooled single-disk, and liquid-surface-cooled double-disk [5]. The method liquid-edge-cooled is applied in ECRH system on HL-2A. The calorimetric method can be applied on the BN window according to principle of calorimetric method.

In order to obtain the transmission efficiency of ECRH system, a calorimeter installed on the output window of gyrotron and the window near launcher separately. The material of the window is BN which the same with the window near the launcher. A small part of the power is absorbed by the window when the microwave transmission through it. In commissioning, by measuring the power in DL and absorbed by window, the percent of the power absorbed by the BN window of gyrotron can be got.

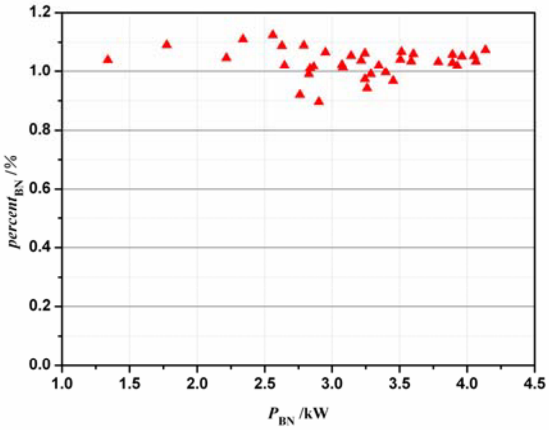

Figure 10. Percentage of the power absorbed by BN window.

As shown in the Fig.10, the percent of power absorbed by BN is 1.05%. The windows of Gyrotron and near the EC launcher are CAD in 140GHz. But the 140GHz systems have not been injected into plasma.

Transmission line in 68GHz system is 7m~10m which include corrugated waveguide, several miter bends, DC break, and sliding waveguide.

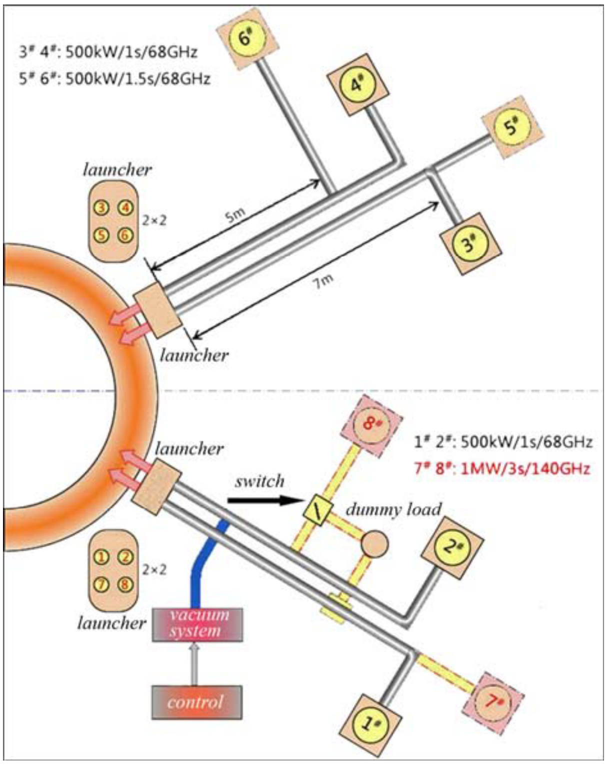

Figure 11. Schematic of ECRH system

The transmission efficiency can be defined as the ratio between the output power of MOU and the power at the end of the transmission line. And the power at the end of the transmission line can be calculated through the percent of power absorbed by window.

By measuring the power at the MOU and BN window near the launcher, we get the transmission efficiency of transmission line is >80% in 68GHz system, as be shown in Fig.12:

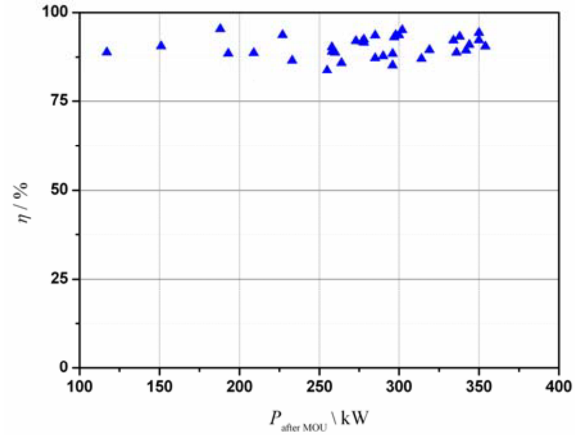

Figure 12. Transmission efficiency of transmission line in 68GHz system

1# to 6# system at 68GHz have been operated many years, in ECRH experiment from the year 2012 to 2013, for example, one of the shots as shown in Table 2. It can be seem that the total power is 2100kW, and duration time is 400ms in this shot.

Table 2. Operation parameters of ECRH 1# ~ 6# systems

Gyrotron	Cathode voltage (kW)	Anode voltage (kW)	Cathode incurrent (A)	Power (kW)
1#	54.5	13.1	21.8	320
2#	53.2	7.1	22.0	500
3#	54.2	15.4	22.1	395
4#	53.7	13.0	20.8	200
5#	54.0	14.9	22.9	355
6#	53.7	15.3	21.0	330

3 Directional coupler

3.1 Principle

Directional coupler is another common way for high power microwave system. Base on the theory of electromagnetic coupling through apertures, directional couplers are being designed.

The rationale of a coupler is that a small part of the microwave power which transmitted in the main waveguide is coupled into the coupled waveguide by a coupled structure, such as multi-holes. The schematic diagram of a coupler is shown in Fig.13:

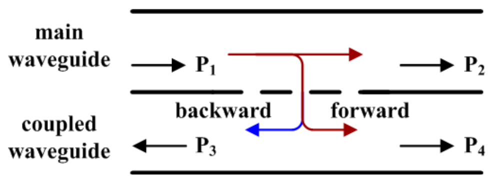

Figure 13. Schematic diagram of a coupler

As shown in Fig.13, the power in main waveguide is P_1. The forward power P_4 can be summed up and backward power P_3 can be minimized by proper designed of the parameters of coupled structure. The coupling factor and directivity are important parameters for the directional coupler.

For the directional coupler we designed, the main waveguide is a corrugated waveguide and the directional couplers will be installed on the miter bend which is used to change the wave direction by 90°, so the injection angle of the microwave in corrugated waveguide is 45°at the miter bend.

The amplitude of the electric field for the i-th coupling hole is expressed as [6, 7]:

$$E_i \propto \omega \cdot a_i^3 \exp\left(-\frac{2\pi}{\lambda} T \sqrt{\left(\frac{1.84\lambda}{2\pi a_i}\right)^2 - 1}\right) \cdot \exp\left[-\frac{x^2}{(\sigma x_0)^2}\right] \quad (6)$$

Where, ω is the frequency of the microwave, λ is the vacuum wave length, a_i is the diameter of the holes, T is the length of the hole, x is the distance from the line of symmetry of the miter bend, and σx_0 is the beam width of the mode in waveguide.

The field intensity of the forward wave which is the contributions of all the holes at the end of the coupled waveguide is given by:

$$E_{fwd} = \mathrm{Re}\sum_{m=1}^{n} E_m \exp\left[i(m)(k_x - k_g)\delta x + i(-k_x + (n)k_g)\delta x + i\omega t\right] \quad (7)$$

Here, n is the total number of the holes, δx is the interval between the holes, k_x is the wave number in the main beam line, and k_g is the wave number in the coupled waveguides. It is obvious that the coupling is the strongest when k_x equals k_g

The field intensity of the backward wave is calculated by:

$$E_{bwd} = \mathrm{Re}\sum_{m=1}^{n} E_m \exp\left[i(m-1)\delta x \cdot k_x + i(m-1)\delta x \times k_g + i\omega t\right] \quad (8)$$

The directivity of the directional coupler is defined as following by using Eqs.(7) and Eqs.(8):

$$D = 10 \cdot \log\left(\frac{E_{fwd}^2}{E_{bwd}^2}\right) \quad (9)$$

3.2 Design of directional coupler

Based on the principle above, we are designing the directional coupler which includes reflecting mirror with one line of coupling holes on it, a coupled waveguide, and a flange. The structure of the directional coupler is shown in Fig. 14:

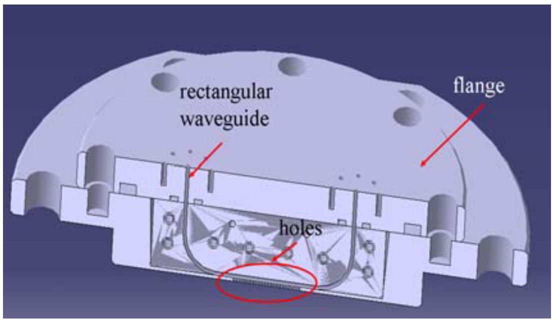

Figure 14. Structure of the directional coupler

The diameter of the holes is gradually decreased from the centre of the holes line to the end in order to achieve a pattern with low side lobes. The hole interval is designed less than $\lambda/2$ to eliminate high order diffraction modes. The structure of holes on the reflect mirror is shown in Fig. 15

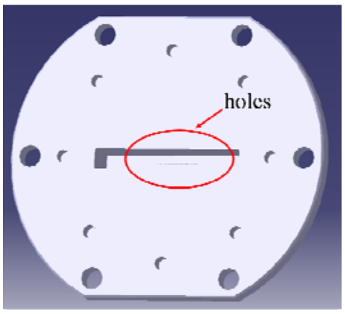

Figure 15. Structure of coupled holes on reflect mirror

The forward wave power will be measured by a detector installed at the end of the coupled waveguide, and a matched termination will be installed at the other end of the coupled waveguide to absorb the backward wave power.

We design directional couplers both for 68GHz and 140GHz system, the design parameters are shown in Table 3:

Table 3 Design parameters of directional couplers

Parameters	68GHz	140GHz
Directivity	50dbB	53dB
Coupling	75dB	77dB
Number of the holes	21	23

4 Summary

Up to now, the ECRH system on HL-2A has been equipped with six 0.5MW gyrotrons at frequency of 68GHz and two 1MW gyrotrons at 140GHz. The 68GHz systems have been operated many years and a few experiment results have been obtained. Power measurement is an important part for ECRH system operation and experimental analysis. Two methods for measuring the power of ECRH system on HL-2A are introduced in this paper which include calorimetric techniques and directional coupler. Calorimetric techniques is an existing technology, which is used successfully in ECRH system commissioning and physical experiments. As a new method the directional couplers have not been used in ECRH system now.

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