Fusion Engineering and Design 133 (2018) 6–18

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Upgrade of ECRH launcher for NTM real-time control on HL-2A tokamak

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ARTICLE INFO

Keywords:
ECRH
EC launcher
NTMs
Real-time control

ABSTRACT

Electron cyclotron resonance heating and current drive (ECRH/ECCD) are deemed to be one of the best option to control the neoclassical tearing modes (NTMs), which are potential danger for steady state operation in fusion reactors. Recently, one of the two ECRH equatorial launchers on HL-2A tokamak has been upgraded to satisfy the real-time control requirements. The upgrade of the rotation and driving mechanism accelerates the tuning speed of poloidal injection angle of EC beam significantly, which permits the modification of the EC power deposition position in real time. Analyses on the beam injection angles and wave power losses, together with calibration results on test bed indicate that the new launcher has a good launching performance. The upgraded No. 2 ECRH launcher was successfully applied in the first proof-of-principle experiment for NTM real-time control, in which within 250 ms suppression of the classical tearing modes (CTMs) by ECRH/ECCD was realized for the first time on HL-2A.

1. Introduction

The electron cyclotron resonance heating and current drive (ECRH/ECCD) are employed worldwide in magnetic fusion devices. With the merit of localized heating, remote control and simple wave-plasma coupling mechanism, it plays an important role in plasma heating, non-inductive current drive, current profile control, MHD instabilities control, assistant start-up and transport study etc. In ITER, a total of 20 MW for ECRH system will be applied in the first phase of auxiliary heating [1]. Controlling neoclassical tearing modes (NTMs) in real time is deemed the basic function of ECRH besides its capability in heating and current drive.

As the coupling medium between EC wave and plasma, the ECRH launcher is a key to reach high efficiency for the goal of ECRH/ECCD experiments. The structure of ECRH launcher is relatively simple compared to the antennas for the other wave heating systems such as ion cyclotron resonant heating (ICRH) and lower hybrid current drive (LHCD). Basically, the EC launchers mainly control two beam parameters, i.e., injection angle and beam size. There are two types of launcher, one is the front steering launcher, using in ASDEX Upgrade [2], DIII-D [3], Tore Supra [4], TCV [5], LHD [6], EAST [7], etc., and the other is the remote steering launcher [8,9]. In HL-2A, two generations of EC launcher have been developed [10–12]. The design of EC launchers on HL-2A uses front steering type for the purpose of intuitive and easy control.

The NTMs may lead to large-scale confinement deterioration, and sometimes even major disruptions [13]. They are growing from the loss of bootstrap current in seeding island at rational magnetic surfaces. By compensating the lost current with external means, the NTMs can be reduced and even completely suppressed. To control the NTMs, ECRH/CD has been widely employed in various magnetic fusion devices, such as ASDEX Upgrade [14], DIII-D [15], JT-60U [16], TCV [17] and FTU [18]. Among them, the fast tunable EC injection has emerged as the mature way to control NTMs.

Since 2003, the HL-2A tokamak has gradually set up 5 MW ECRH systems, including six 68 GHz/0.5 MW/1(1.5)s and two 140(105)GHz/1 MW/3 s sub-systems. The ECRH system has made important contribution to the HL-2A experiments, including realizing a record of 5 keV for the electron temperature [19,20]. The present layout of the ECRH system is shown in Fig. 1, in which the eight sub-systems use two equatorial launchers to inject the EC power into plasma.

In order to realize the real-time control of NTMs on HL-2A, the No. 2

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https://doi.org/10.1016/j.fusengdes.2018.05.074
Received 29 January 2018; Received in revised form 17 May 2018; Accepted 22 May 2018

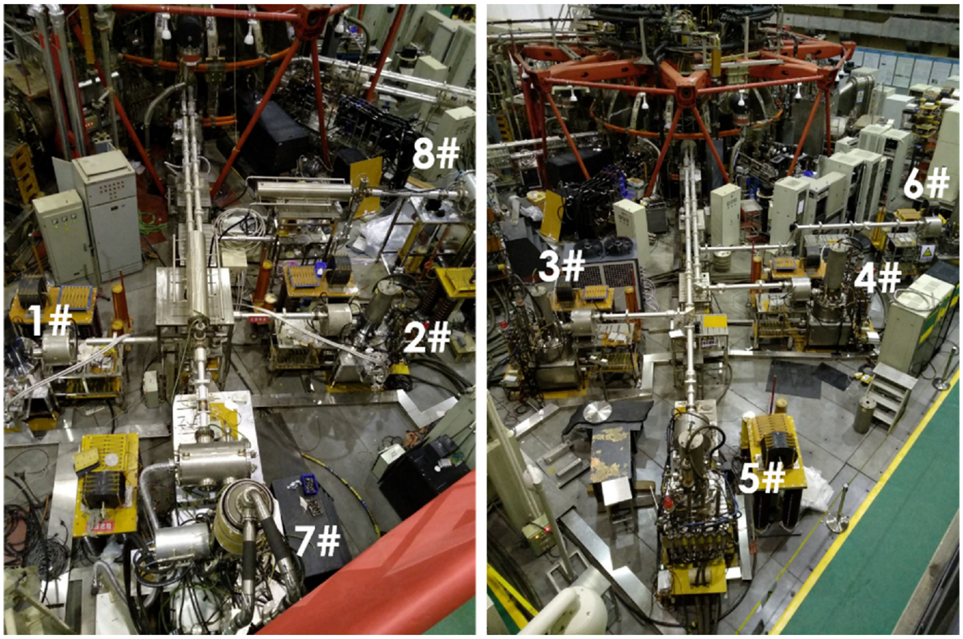

Fig. 1. Layout of the 5 MW ECRH system on HL-2A tokamak. Left: No. 1–2 & 7–8 sub-systems; Right: No. 3–6 sub-systems.

launcher has recently been upgraded to have fast tuning capability for poloidal injection angle. At the same time, the diagnostics on the Mirnov coils [21] and ECE [22] have been utilized for real-time detection of the islands, and a new system named RT PARC (Real-Time Plasma shApe ReConstruction) [23] has been set up to acquire the equilibrium data in real time. Based on these developments, a new system for NTM real-time closed loop feedback control has been constructed. In HL-2A experiments, NTMs have been observed triggered by sawteeth crash [24]. However, the formation of NTMs needs harsher conditions compared to the classical tearing modes (CTMs). Hence, the CTMs are chosen as the best alternative target for proof-of-principle experiment. With this system, first experiment for real-time control of CTMs has been done successfully.

This paper reports the recent upgrade of the ECRH launcher and its performance during the CTM real-time control experiments. The remaining sections are arranged as follows. Section 2 gives a brief introduction to the ECRH system and details of the upgrade design of the No. 2 launcher. Section 3 presents the details about the NTM real-time control related software and hardware and also the calibration work for the beam injection angle. Section 4 introduces the experiment on real-time control of tearing modes based on the upgraded launcher. The final Section 5 is devoted to the summary to this work.

2. Upgrade design of the No. 2 launcher

The HL-2A tokamak is a medium size tokamak with the major radius $R = 1.65$ m and minor radius $a = 0.4$ m. The general parameters for HL-2A are as follows, the plasma current is $I_p \sim 150$–450 kA, the magnetic field is $B_t \sim 1.2$–2.7 T, the electron temperature is $T_e \sim 0.5$–5 keV. In the real-time experiments, the 68 GHz ECRH system is used, and the magnetic field is set to be $B_t \sim 1.2$–1.4 T, so that the 68 GHz ECRH system works at second-harmonic heating regime. For the 5 MW ECRH system, two launchers are used to inject the wave power, in which the No. 1 launcher is used to inject 2 MW/140(105)GHz/3 s and 1 MW/68 GHz/1 s power, while the No. 2 launcher is used to inject 2 MW/68 GHz/1 s power [19,20]. The two launchers both have the ability of tuning the injection angle poloidally and toroidally. The injection angle is allowed to be adjusted between shots. For the NTM real-time control purpose, the No. 2 launcher has been upgraded to speed up the time response of the poloidal injection angle. Detail work is shown below.

2.1. Structural design

On HL-2A the 2/1 tearing mode magnetic islands have a typical size of 4–8 cm. To have better effect on control, the deposited power and driven current need to be located inside the magnetic islands [25], which means good alignment of EC deposition (for both localized heating and current drive) with magnetic islands to be necessary. Therefore, the real-time control of CTM/NTM requires narrow EC power deposition and accurate beam injection angle. Besides, the position of the magnetic islands may change in the process of wave-island interaction, which means the launching angle has to be adjusted in real time. On HL-2A it is frequently observed that the 2/1 magnetic island change from $\rho \sim 0.5$ to $\rho \sim 0.7$ in 100–200 ms and vice versa. It is thus necessary to design an ECRH antenna capable of tracking the position of the magnetic island in comparable response time.

Fig. 2 shows the structural design of the new No. 2 ECRH launcher. The main body of the launcher is made of stainless steel. Viewing from the side of transmission line, the front part of the launcher is connected to a transitional circular sleeve to the Φ350 mm tokamak equatorial port. The rear part of the launcher is connected to four transmission lines with the inner diameter of 80 mm. A vacuum box is used as the main structure and container for inner components. Its rear part has an outline of playground runway, which can enlarge the room to contain all the inner components and also consolidate the structural strength. The front part of vacuum box is round in accordance with the transitional section.

Inside the vacuum box, there are four focusing mirrors and two steerable mirrors. With this compact design, the launcher transfers four beams carrying 500 kW power lasting for 1 s from the transmission lines to the plasma through the tokamak port. The four beams pass through the Boron-Nitride (BN) windows, focus and deflect by 90° at the focusing mirror, reflect at the steerable mirror, and then head towards the tokamak plasma. The new design inherits the previous design to have triangular shape for the steerable mirrors, which can combine two beams to mitigate the narrow space problem. In particular, the new design upgrades the rotation and driving mechanism for the steerable mirrors and also some other design details. The variation of the poloidal and toroidal injection angles are realized by the steerable mirrors and their driving mechanism. Outside the vacuum box, four stainless steel bellows are used to enable the movement of driving mechanism and to