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Mechanical and quasi-optical design of ECH/ECCD launcher for JT-60SA

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HIGHLIGHTS

- We designed high-power, long-pulse, two-frequency launcher for JT-60SA.
- The mirror steering structure was improved for easy maintenance.
- A full scale mockup of the steering structure moved smoothly.
- It was found that the antenna is suitable for two frequency operations.
- The total spillover loss of ~1% was obtained with LP11even mode of 10%.

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ABSTRACT

Mechanical and quasi-optical design of an electron cyclotron heating/current drive launcher for JT-60SA is in progress. A full-scale mock-up of the steering structure, which enables linear and rotation motions of the first mirror of the launcher, has been fabricated for cyclic test of the bellows part. Moreover, an improved design enables easy replacement of the bellows for rotation for maintenance. Quasi-optical characteristics of the antenna mirrors have been studied to evaluate its transmission efficiency and beam focusing property. In calculation, it was found that the antenna is applicable to two frequency operation at 110 GHz and 138 GHz. It was quantitatively shown that the transmission efficiency of ~99% (not including Ohmic loss) is obtained even with the higher order mode (LP_{11}^{even}) fraction of 10% by optimizations of the shape of the first mirror. These results contribute to optimization/finalization of the launcher design toward fabrication of the launcher for JT-60SA.

1. Introduction

An electron cyclotron heating (ECH) and current drive (ECCD) system is recognized as an important tool for fusion experiments. In JT-60SA (Super-Advanced), which is an upgrade of JT-60U, main roles of the ECH/ECCD system are localized electron heating and current drive to suppress neoclassical tearing modes (NTMs), to control temperature and current profiles, start up assist and EC-wall cleaning [1]. The required power and pulse length of the system are 7 MW (to plasma) and 100 s, respectively. Four launchers will be installed into tokamak through upper oblique ports of the cryostat and the vacuum vessel. Each launcher has two/three waveguide transmission lines connected to each 1 MW gyrotron, which will be operated at two frequencies of 110 GHz and 138 GHz [2]. Since high-power, long-pulse millimeter wave injection is required, active cooling of the antenna mirrors is essential. Moreover, wide range of steering capability is required in both poloidal and toroidal directions. In order to minimize risk of water leakage in the vacuum vessel with the required steering capability, a linear-motion (LM) antenna was proposed [3]. A conceptual design and a mock-up test of a part of the steering structure and low power tests of a LM-antenna were carried out [4–7]. Recently, detail design and mock-up test are in progress toward finalization of the launcher design; the launcher will be fabricated and installed in 2016–2018 prior to the first plasma in March 2019.

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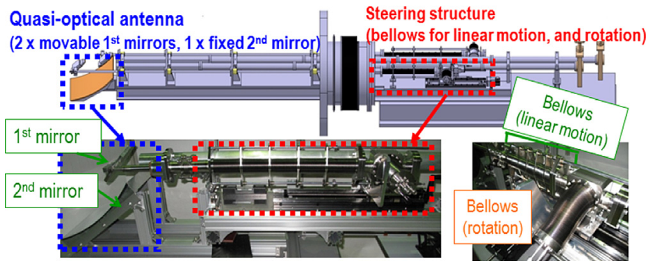

Fig. 1. CAD model of the ECH/ECCD launcher and the full scale mockup of the quasi-optical antenna part (one set of waveguide and first mirror) and the steering structure.

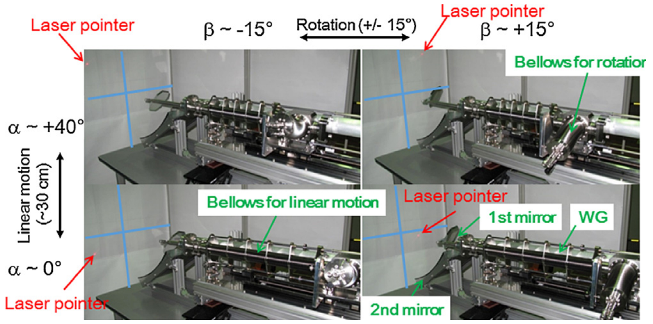

Fig. 2. Schematic view of the ECH/ECCD launcher and the mock-up of the steering structure. Long-stroke (~3 m) shaft and bearing are not included.

In this paper, we describe results on the mechanical design and development using a full scale mock-up, and a numerical study of quasi-optical characteristics of the antenna mirrors for detail design of the mirror shape to minimize diffraction loss.

2. Mechanical design and mock-ups

An important function of the ECH/ECCD system is a control of the heating/current drive position with high accuracy. The launcher of the JT-60SA ECH/ECCD system (Fig. 1) is featured by a concept of the mirror movement enabling poloidal and toroidal steering. The poloidal beam injection angle is altered by a linear motion of the first mirror (M1) by changing injection angle to the second mirror (M2), which is fixed curved mirror [3]. On the other hand, the toroidal beam injection angle is altered by a rotation motion of the M1 around the driving shaft of the M1 [5]. The linear motion of ~306 mm corresponds to the required poloidal beam scan of ~60°, and the shaft rotation by 30° directly corresponds to the required toroidal beam scan of 30°. The present targets of speed of mirror movements are ~6.5 s and ~1 s for full poloidal and toroidal scans, respectively. Key components of the steering structure are the long-stroke bellows for linear motion; the bellows for shaft rotation; the bearing structure supporting both linear and rotation motions; and the long-stroke shaft involving two (in/out) cooling water lines. The basic principle of its movement was confirmed by a partial mock-up of the bellows structure [6], and one candidate of the bearing structure using solid lubricant was tested [7]. In order to confirm its reliability and fabrication process, full scale mock-up of the bellows structure with an improved design has been fabricated as shown in Fig. 1, and its movement has been confirmed with a mock-up of the quasi-optical antenna part (Fig. 2). It was confirmed that the laser pointer injected into the waveguide was reflected by the M1 and M2, and the position of the laser on the target screen was moved both in poloidal and toroidal directions by linear and rotation motion of the M1. The long-stroke bellows and the bellows for rotation worked as expected. It is noted that the range of the movement shown in Fig. 2 is limited by a size of the target while the required movements in linear (400 mm) and rotation (±20°) were successfully confirmed both in vacuum and atmospheric conditions.

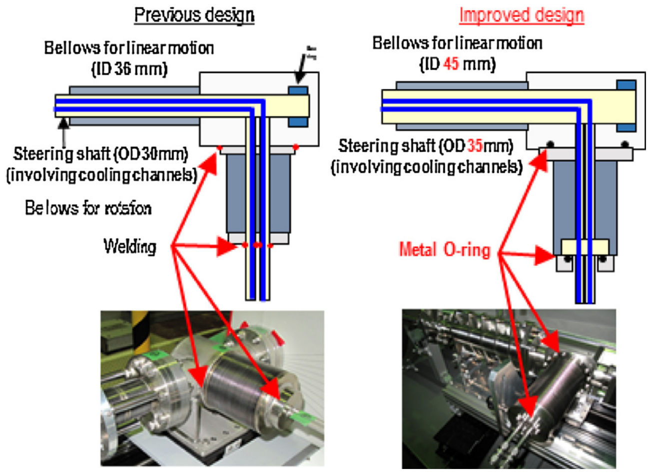

Fig. 3. Previous (left) and improved (right) bellows structures.

Fig. 3 shows metal O-ring structure adapted to an improved design. The bellows for rotation of the previous design tested by the partial mock-up was welded to the vacuum chamber involving the driving shaft. Consequently, it was required to cut the bellows and the cooling channels of the steering structure if the case of vacuum leakage at the bellows. The improved design enables to replace this bellows without cutting the cooling channels and the bellows. Thus quick and easy maintenance is possible. The long-stroke bellows for linear motion was also re-designed to increase inner diameter so that the diameter of the driving shaft is increased from 30 mm to 35 mm to increase its rigidity. In order to confirm its reliability, a cyclic test of 10^5 cycles for linear motion and 10^4 cycles for rotation is under preparation. This cyclic test needs about one month of continuous operation and it will be finished in December 2014.

Other mock-ups of the long-stroke shaft with a bearing structure, and the large curved mirror involving internal cooling channels to be fabricated by hot isostatic pressing technology are also under fabrication to confirm reliability and fabrication processes. These design and mock-up tests are important process to confirm its feasibility prior to the fabrication of the launcher.

3. Quasi-optical design

3.1. *Two frequency operation*

In the previous works [4–6], the conceptual design study of the launcher was carried out by assuming the frequency of 110 GHz and the target plasma at 1.7 T. The target toroidal beam steering angle range was −15° to +15°. Recently, a dual-frequency gyrotron operated at 110 GHz or 138 GHz has been developed in JAEA [8]. It enables ECH/ECCD at various positions in plasmas at both the toroidal magnetic field of ~1.7 T and ~2.3 T. In order to clarify the quasi-optical characteristics of the antenna at 138 GHz, we calculated the beam injection angle range and the beam power profiles by a numerical code used in the previous work [4].

Since the target plasma and magnetic field are different, the toroidal injection angle larger than +20° is suitable to obtain higher ECCD efficiency in co-direction for the scenario-2 of JT-60SA, which is the scenario for the maximum plasma current of 5.5 MA and the maximum toroidal field of ~2.3 T [9,10]. On the other hand, the mechanical limitation of the steering structure of the launcher is 30° in the toroidal direction. Moreover, if the M1 is rotated to $\beta > 15°$, the spillover at M2 is significantly increased, and not