Fusion Engineering and Design 86 (2011) 763–767

Contents lists available at ScienceDirect

Fusion Engineering and Design

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

Progress in ECRF antenna development for JT-60SA

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ARTICLE INFO

Article history:
Available online 24 February 2011

Keywords:
ECRF
Antenna
Linear motion
Mock-up
Poloidal and toroidal angles
JT-60SA

ABSTRACT

Structural, mechanical and optical design work on antennas/launchers for the electron cyclotron range of frequency heating and current drive system in JT-60 Super Advanced (JT-60SA) have been advanced based on a linear motion antenna concept. A CAD model of the launcher was built with realistic component sizes. A mock-up of the steering structure consisting of two different bellows sections for poloidal and toroidal beam scanning was fabricated to test movement of the bellows. The poloidal (-40° to $+20^\circ$) and toroidal (-15° to $+15^\circ$) injection angle ranges required in JT-60SA were shown to be realized by this steering structure and mirrors.

1. Introduction

Development of antennas/launchers for the electron cyclotron range of frequency (ECRF) system for JT-60 Super Advanced (JT-60SA) [1] is ongoing. In this paper, the word “antenna” is used from the optical standpoint (the mirrors) while the word “launcher” is used from the structural standpoint. Four launchers will be installed into four upper oblique ports (port numbers P1, P4, P8, and P11) of the JT-60SA tokamak. Two of them will be installed before the first plasma discharge, which is planned in 2016. The other two will be installed for the Integrated Research Phase, which will be started a few years after the first plasma discharge. A pulse length capability of 100 s, which requires active cooling for the antenna mirrors, and flexibility of the beam injection angles in both the poloidal and toroidal directions are required, and must be highly reliable. Conceptual design of the antenna based on a linear motion (LM) antenna concept [2] had been carried out previously [3]. The LM antenna features simultaneous realization of (a) a wide poloidal injection angle range by means of only the linear motion of a small mirror, and (b) reduction in the risk of water leakage in the vacuum vessel by eliminating flexible tubes for coolant.

In this paper, we present our progress in mechanical, structural, and optical design work on the ECRF antennas/launchers for JT-60SA. In the previous work [3], we mainly discussed only the capability of poloidal beam scanning under the LM antenna concept, while in this paper we discuss two-dimensional (both toroidal and poloidal) beam scanning. The mechanical structure to enable two-dimensional beam scanning was studied using CAD and a mock-up. The optical properties were studied numerically. In Section 2, the design conditions and outline of the overall system of the ECRF launcher/antenna are described. The mechanical and optical designs are presented in Sections 3 and 4, respectively. The results of the mock-up experiment are also provided in Section 3.

2. ECRF antenna/launcher

The design parameters of the JT-60SA ECRF antenna/launcher are shown in Table 1. The parameters marked with an asterisk (*), and especially the optical design parameters, are tentative values and will be further discussed before the design is finalized. The values in Table 1 are being used as targets in this design work. The port size on the vacuum vessel is 480 mm × 480 mm while the port on the cryostat, which is the interface between the tokamak and the ECRF launcher, is larger than 1 m × 1 m; the size of the launcher must be smaller than 480 mm × 480 mm so that the launcher can be installed and uninstalled after the tokamak is assembled. The angle of the port is 35.5° with respect to the horizontal plane.

Fig. 1 shows a model of the present launcher design. The antenna portion is placed on the inside of the vacuum vessel and the edge of the antenna is located just behind a stabilizing plate (with a first wall), which is installed at the outboard side of the plasma to stabilize resistive wall modes. The distance from the inner edge of the

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doi:10.1016/j.fusengdes.2011.01.060

Table 1
Design parameters of the ECRF launcher in JT-60SA.

Parameters	Values
Port size	480 mm × 480 mm (at narrower duct) ~3 m (length)
Aperture size	680 mm × 580 mm (at stabilizing plate)
Port angle	35.5° (from horizontal plane)
Location (*R*, *z*)	(4073, 895) (at the center of the aperture on the stabilizing plate)
Target beam direction range (*)	Poloidal (θ_p) −40° to +20° Toroidal (θ_t) −15° to +15°

stabilizing plate to the edge of the antenna, which is the edge of the large-sized curved mirror (M2), is assumed to be about 50 mm in the direction parallel to the port axis. Because the first wall on the stabilizing plate is expected to block the SOL plasma in front of the antenna, the heat flux into the antenna mirrors from the SOL plasma will be small compared with that into the first wall. The size of the aperture at the stabilizing plate is 680 mm (width) × 580 mm (height). The mechanical structure that allows movement of the first mirror (M1) is placed on the outside of the cryostat as shown in Fig. 1(b). The length of the launcher in the vacuum vessel is about 3 m. The launcher is installed on an inclined stage, which stands on the floor of the building just beside the cryostat, and the launcher is a cantilevered from it. The design of the stage is ongoing and beyond the scope of this paper.

Although the target injection angles in both the poloidal (θ_p) and toroidal (θ_t) directions are tentative, they are defined to cover the ranges for the following important roles in the present study. The injection to the q = 2 surface, which is required for neoclassical tearing modes stabilization [4], is expected to be realized at $\theta_p = -5°$ to +5°, i.e., it is located at $\rho = \sim 0.6$ in the JT-60SA scenario 5 [1]. Here, q and ρ are a safety factor and the minor radius of the plasma, respectively. Where θ_p is approximately −35°, the ray goes to the plasma

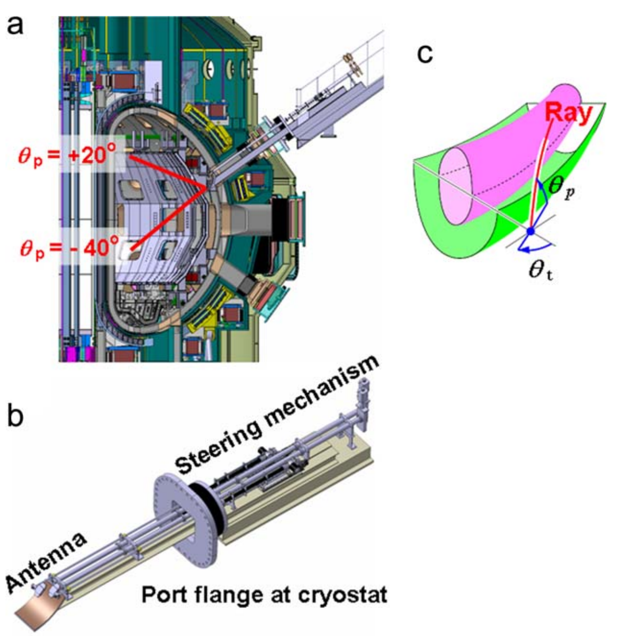

Fig. 1. CAD model of the ECRF launcher for JT-60SA. (a) The poloidal cross-section of the JT-60SA tokamak where one of the ECRF launchers is installed. (b) An ECRF launcher consisting of the antenna portion inside the vacuum vessel and the steering mechanism outside the vacuum and support structures. (c) Definition of the toroidal and poloidal injection angles.

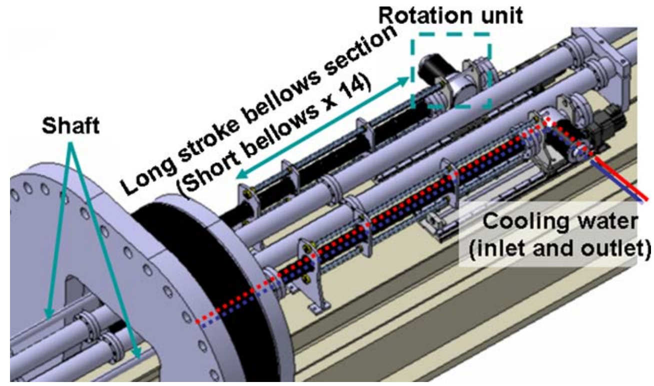

Fig. 2. Schematic view of the steering mechanism. A rigid shaft connected to the M1, which includes cooling water lines (inlet and outlet), is contained in the long-stroke bellows section and bended at the rotation unit.

center. A θ_t of approximately +15° is required for maximizing ECCD current, $\theta_t = 0°$ is used for pure electron heating, and negative values of θ_t are used for counter ECCD experiments. The definition of θ_p and θ_t are the same as those in the ray tracing code [5] as seen in Fig. 1(c). The relation between α in the conceptual design [3] and θ_p is $\theta_p = \alpha - 35.5°$ for $\theta_t = 0°$ ($\beta = 0°$), and this is slightly different for $\theta_t \neq 0°$.

3. Mechanical design for two-dimensional beam scanning

Active cooling for steering mirrors is required for a long pulse and high power ECRF antenna and a front steering antenna/launcher concept with flexible coolant tubes is widely adopted [6–9]. However, the LM antenna has been proposed to reduce the risk of water leakage in the vacuum vessel due to problems with the flexible coolant tubes, and it has no flexible part for coolant in the vacuum vessel. Cooling water flow is via a rigid pipe made of stainless steel and the movement of the pipe is absorbed by bellows at the vacuum–atmosphere boundary. The cooling water does not touch the bellows directly. The flexible water line is only in the atmosphere environment. There is a risk of vacuum leakage at the bellows; there is, however, less risk of water leakage in the vacuum. Moreover, accessing the bellows section, which is placed at the end of launcher (outside the tokamak), for maintenance is relatively easy compared with accessing a flexible coolant channel installed near the front steering mirror. Therefore, this antenna design reduces the risk of water leaks inside the vacuum vessel leading to lengthy interruptions in tokamak operation.

Fig. 2 shows a schematic view of the steering mechanism with two transmission lines. A rigid shaft that contains two lines for coolant (input and output) is connected to the M1 in front of the waveguide in the vacuum vessel. The outer diameter of the shaft is 30 mm. Via the straight long-stroke bellows section (for poloidal beam scanning), the shaft is bended, and rotated in the rotation unit (for toroidal beam scanning) as described below.

3.1. Poloidal beam scanning

In order to scan the poloidal injection angle, the small mirror (M1) in front of the waveguide is moved linearly on the axis of the waveguide. The required stroke of the linear motion is 356 mm in the present design for $\theta_p = -44.5°$ to +24.5° at $\theta_t = 0°$. Although it is slightly dependent on the optical design, at least 300 mm is required. In order to attain this, a straight long-stroke bellows, having a total length of about 1 m, is required. The launcher angle of 35.5° may cause a small deformation of the bellows due to the weight of the bellows itself, and the fast linear motion may cause inhomogeneous stress to the bellows. In order to reduce