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Design status of the ITER ECRH upper launcher mm-wave system

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ABSTRACT

The purpose of the ITER electron cyclotron resonance heating (ECRH) upper launcher (UL), or antennae will be to provide localised current drive by accurately directing mm-wave beams up to 2MW, out of the four allocated upper port plugs, at chosen rational magnetic flux surfaces in order to stabilise neoclassical tearing modes (NTMs). This paper will present an overview of the UL, with emphasis on the mm-wave components. The mm-wave layout includes corrugated waveguide sections and a quasi-optical path with both focusing mirrors and plane steering mirrors. One of the essential components of the UL is the Steering Mechanism Assembly (SMA), providing variable poloidal injection angles fulfilling high deposition accuracy requirements at the plasma location. The Actuator principle and rotor bearings are frictionless and backlash free, avoiding tribological difficulties such as stickslip and seizure. The underlying working principle is the use of mechanically compliant structures. Validation and proof testing of the steering principle is achieved with an uncooled first prototype demonstrator. A second prototype is currently being manufactured, comprising the functionalities needed for the ITER compatible system such as water cooling and high power mm-wave compatibility. In order to perform the fatigue tests of the actuator bellows, a test facility has been built, under ITER-like vacuum and temperature working conditions. Results of the cyclic fatigue tests are compared to the various manufacturer standards and codes, combining stress and strain controlled material fatigue properties.

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1. Introduction

The Electron Cyclotron Heating and Current Drive (ECH&CD) system for ITER is planned to consist of 24 MW installed power at 170 GHz and an additional 3 MW (∼3 s) at ∼127 GHz for assisting in plasma breakdown. This power is generated from a set of up to 27 gyrotrons and transmitted via evacuated 63.5 mm HE_{11} waveguide lines (∼100 m in length) to two launching systems: one Equatorial Launcher (EL) [1] and four upper launchers (UL) [2]. The choice of the launchers depends on the physics application. In-line switches direct the power to the appropriate launchers. For example, the EL is used when a more central deposition is desired (inside mid radius), while the UL is used for control of MHD activity (accessing outer two thirds of plasma cross-section).

This paper provides a review of the UL design activities associated with the mm-wave system. An overall review of the mm-wave system design is provided in Section 2, followed by a brief description of the steering mechanism assembly design and prototype manufacturing progress. Section 4 provides a summary of the test program of the various components used in the UL design, followed by a conclusion.

2. General aspects

The primary aim of the UL is to direct the mm-wave beams into the plasma for the control of plasma instabilities that can occur on rational magnetic flux surfaces typically located in the region of the outer half of the plasma volume. These instabilities have the potential to reduce the fusion yield by 50% and can be eliminated using a very peaked and narrow driven current on or near the relevant flux surface. Thus, the UL must provide a steerable and well focused beam over the range in which these instabilities occur.

These functions are achieved via an optical mm-wave transmission system that includes a combination of waveguides, free space focusing mirrors and a steering mirror. In free space, the variation of the electric field amplitude transverse to the direction of propagation is admitted to be of Gaussian form with the half-width to the $1/e$-contour value being equal to w, defined as the *beam radius*. A

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well focused beam is achieved by starting with a beam leaving the circular waveguide (∼60–80 mm diam.) in the port plug (volume of the UL), which is then focused to a small beam width (between 20 and 30 mm) at a distance of up to 2 m in the plasma. The larger the beam in the port plug the more focused the beam can be achieved in the plasma for a more efficient system (or requiring less injected power) for stabilising the plasma instabilities. However, the port plug has to be confined within the available space of the ITER upper port extension and this space is shared with the port plug structure [10], shield blocks [12] and auxiliary systems (cooling and control systems). Thus there is a practical limit to the size of the mm-wave beams and the associated components.

The optical design is achieved in an iterative process between physics analysis (defining the optimum beam parameters), the designers of the port plug structure (optimising the available space) and the nuclear analysis (to ensure sufficient shielding to avoid high neutron streaming rates through the port plug). The configuration has a "dog-leg" introduced into the path of the beam, which improves the orientation of the beam and avoids a direct line of sight through the port plug to limit neutron streaming. Remote handling aspects are also being taken under consideration, and are under progress [11].

2.1. mm-wave design

Two optical configurations have been investigated to date: mitre bend and quasi-optical.

The mitre bend design from 2006 [5] includes two mitre bends per beam path that form the "dog-leg" followed by a focusing and a steering mirror, each shared by four beams (Fig. 1). The advantage of the mitre bends is that the stray radiation is minimised in the back half of the launcher as the RF power can not radiate out of the waveguide. The disadvantages are: the mitre bends and waveguides need active cooling (note that the highest peak power density occurs on the mitre bends), additional complexity associated with installing the waveguide components, limited flexibility in optimising the optical design and a relatively large amount of stray radiation directed toward the front of the launcher. Despite the above disadvantages the mitre bend design is compatible with the ITER port plug and shield requirements.

The quasi-optical design (Fig. 2), replaces the mitre bends with two free space mirrors, each with four incident beams. In the present design of the optical path, the four separate M2 mirrors per row share a common support structure. The ongoing optimisation work of the mm-wave transmission aims at defining a single plane surface for the two rows of M2 mirrors and possibly a single focusing

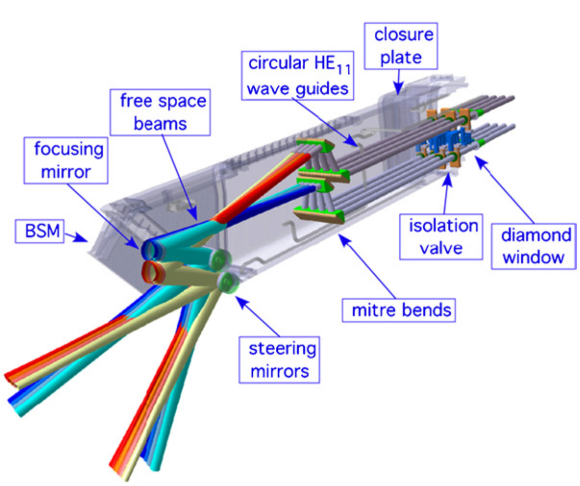

Fig. 1. ITER EC upper launcher. mm-wave system, Mitre bend case.

M1 mirror for each row of four beams. However, the optical optimisation has to minimise the peak heat load on the mirror and the astigmatism, and maintaining appropriate polarisation. The guided mm-wave components consist of the following components: HE_{11} waveguide, waveguide-to-window adapters, in-line isolation valve, SS waveguide coupling, HE_{11} to TEM_{00} converters. The last section of waveguide will use a tapered section that converts the HE_{11} mode into a predetermined set of HE_{1n} modes for a more optimised coupling between the guided and free space (TEM_{00}) modes, reducing the stray power and increasing the overall transmission efficiency of the launcher. Note that the "dog-leg" configuration is maintained, which avoids neutron streaming up the transmission lines. This beam description is in the process of being installed into the CAD environment (CATIA). A complete quasi-optical design is nearing completion and is expected to be the reference design of the UL.

3. Steering mechanism assembly (SMA)

One of the essential components of the UL is the steering mechanism assembly (SMA) [6,7], providing variable poloidal injection angle and small amplitude modulation fulfilling high deposition accuracy requirements at the plasma location. In the adverse invessel operating conditions, reliable operation is required to guarantee the availability of the SMA during the 20-year lifetime of ITER. The Actuator principle and rotor bearings are therefore frictionless and backlash free, avoiding tribological difficulties such as stickslip and seizure. The underlying working principle is the use of mechanically compliant structures.

Validation and proof testing of the steering principle is achieved with an uncooled first prototype demonstrator (Fig. 4). A second prototype (Fig. 5) is currently being manufactured, comprising the functionalities needed for the ITER compatible system such as water cooling, materials and high power mm-wave compatibility.

The actuator system is based on four externally helium pressurised bellows working against six helicoidal, machined, preloaded, compressive springs (Fig. 3). This allows the mirror (not shown on this figure) a rotation of 14° around two flexure pivots (±5.5° required for the mirror rotation, and ±1.5° to compensate manufacturing inaccuracies and misalignments in the UL). One side of each spring is captured on the stator (fixed parts) and the other side on the rotor (moving parts).

Based on energy confinement, sawtooth time scales, on the burn cycles and pulse lengths, the number of steering mirror rotations during the whole life of ITER are estimated as 21,000 full cycles (±5.5°) and 840,000 partial cycles (±2°) at any position within the steering range [2]. The desired steering accuracy has been determined by physics requirements to ±0.05°.

The EM forces related to the induced currents during a Vertical Displacement Event (VDE) were estimated for the steering mirror in the worst configuration and assuming no shielding effect from the port wall, $\Delta B_P/\Delta t = 25T/s$ ($I_P = 17.85MA$ and $\Delta t_{disrupt} = 0.04s$) and $B_T = 5.0T$. The resulting net torque on the steering mirror is 354 Nm. The flexure pivots are dimensioned to withstand the resulting radial forces.

3.1. 1st prototype

As mentioned previously, the steering mechanism is based on a novel concept replacing the traditional ball bearings and push-pull rod actuator with a set of flexure pivots and a bellows–spring actuator. The objectives of this first prototype system are the following:

- Demonstrate a functional steering mechanism using the bellows–spring actuator in a similar steering mirror assembly as envisioned for the ITER UL.

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