Design of the Remote Steerable ECRH launching system for the ITER upper ports

A.G.A. Verhoeven, B.S.Q. Elzendoorn, W.A. Bongers, A. Bruschi2, S. Cirant2, I. Danilov1, A. Fernandez5, G. Gantenbein3, M.F. Graswinckel, R. Heidinger1, W. Kasparek3, K. Kleefeldt1, O.G. Krujit, B. Lamers, B. Piosczyk1, B. Plaum3, D.M.S. Ronden, G. Saibene6 and H. Zohm4

FOM-Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Trilateral Euregio Cluster, Nieuwegein, The Netherlands, www.rijnh.nl/ITERECRH, 1Forschungszentrum Karlsruhe, Association FZK-EURATOM, 2CNR, Milan, 3Univ Stuttgart, 4Max-Planck, Garching, 5Ciemat, Madrid, 6EFDA, Garching

verhoeven@rijnh.nl

Abstract. An ECRH (electron-cyclotron resonance heating) launching system for the ITER upper ports is being designed. The aim of the system is to inject Electron Cyclotron Waves (ECW) in the ITER plasma in order to stabilize neoclassical tearing modes (NTM). Each of the four upper-port launchers consists of six mm-wave lines capable of transmitting high power up to 2 MW per line at 170 GHz. In order to exploit the capability of ECW for localized heating and current drive over a range of plasma radii in ITER, the ECH&CD upper port launcher must have a beam steering capability. The Remote Steering (RS) principle has great advantages, because it enables to avoid steerable mirrors with flexible cooling lines at the plasma-facing end of the launcher. The principle consists of a long, corrugated, square waveguide having the steerable optics placed outside of the first confinement boundary of the vacuum vessel. All vulnerable components are far away from the hostile plasma environment. Furthermore, the RS launching system enables to do maintenance on the system during shutdown, without affecting the torus vacuum and the blanket cooling circuits.

1. System lay-out
Starting from the gyrotrons, the mm-wave power will be transmitted towards the tokamak by circular evacuated waveguides with an aperture of 63.5 mm. Steering of the beam over a range of +/- 12° will be achieved by a mirror system consisting of a combination of curved and rotating mirrors. Via the mirror system the beam will be directed into a square corrugated waveguide of 44x44 mm with a length of 4.4 m. A single-disk diamond window and an isolation valve will provide the tritium boundary between the primary and secondary vacuum. At the end of the square waveguide, mm-wave beams will be guided through penetrations in the front-shield blanket module by a set of 2 fixed mirrors towards the ITER plasma. The mirrors will have focusing properties in both directions. This will result in an effective steering range in the plasma such that all the flux surfaces can be reached at a major radius of the ITER plasma of 5650 mm at horizontal locations between 1900 and 3300 mm. The latest 3-D CATIA model (June 2005) incorporates the newest requirements on steering range and launching angles, following from recent physics-based performance analysis [1,2].
2. Design parameters
At the start of this work, we came to the reference model. This is now obsolete, but a good indication of how the work evolved from the start, where the design was based on 3 ports, each carrying 8 beam lines at a frequency of 170 GHz. In the reference model a single end mirror directed the beam to the proper position in the plasma by focusing the beam in both directions, poloidal and toroidal. The input scanning range was set at ±12°, the maximum that can be handled by the remote-steering square waveguide. Both the angles $\alpha$ (the poloidal launching angle, the angle between the poloidal component of the nominal beam centerline and the horizontal plane) and $\beta$ (the toroidal launching angle, the angle between the nominal beam centerline and its poloidal component) were set in the way as given by the beam tracers [1,2]. The resulting $\alpha$ scan in the plasma covered the full range for all the ITER scenarios. The angle $\beta$ was optimized as follows: upper row: $-18^\circ$, lower row: $-20^\circ$ [3,4].

The 2-MW ECRH mm-wave system has to operate under various vacuum conditions. The transmission line is partly quasi optical, at the location of the remote steerable mirror and at the location of the plasma facing fixed mirror, see fig.1. As the primary vacuum boundary a diamond window is placed after the steerable mirror in order to prevent tritium and beryllium contamination. Maintenance on the system after DT operation is foreseen, depending on the resulting neutron load in the port-duct [5]. Behind the diamond window an isolation valve and the entrance of the square corrugated waveguide are located.

3. Mirror steering mechanism
As it leaves the gyrotron, the mm-wave beam is guided through a waveguide with a circular cross-section of 63.5 mm. Steering of the beam is achieved by a steerable mirror mechanism, placed at the end of the circular waveguide, see fig. 2, top. The scanning plane orientation of the outgoing beam plane determines the plane of steering at the input. For the newest layout, the dog-leg, the scanning plane is almost vertical, see chapter 6. The spot size at the beginning of the square waveguide has to be limited, therefore a fixed, curved mirror (M1) will focus the beam. The steerable mirror (M2) makes a combined translating and rotating movement in the drawing plane in order to steer the beam through the waveguide aperture.
The initial set-up was so that the beam axis crosses the waveguide axis always at the point of entry of the waveguide. The way to achieve this is to let the mirror rotate around the mirror midpoint, located on the (flat) mirror's surface (axis perpendicular to the sketch surface), combined with a simultaneous translation along the incoming beam direction (vertical, as seen in figure 2). By using a cam-mechanism, only one actuator is needed to perform both movements, simultaneously.

An alternative to the current design is under examination, to allow for the scanning-angle dependency of the waveguide length. The effective length of the waveguide can be defined as the length from the crossing point of the beam with the axis of the waveguide to the end of the waveguide. There is a mechanism for changing the effective length while steering. By altering the CAM profile of the steerable mirror unit somewhat, the location of the crossing point between the beam and the waveguide axis can be changed. With this flexibility a profile can be designed that enables to optimize the length of the waveguide for all steering angles. The optimized cam profile also takes into account the effect of beam scrape-off at the (limited-size) diamond window [6]. Although the mm-wave beam enters the diamond window under angles as large as 12 degrees, the maximum reflection on the window is always lower than 1%.

4. Reference model
For the reference model the single-end- mirrors in the front shield direct the beam under the required angles $\alpha$ and $\beta$ into the plasma, while focusing the beams in both planes.

The mirrors are elongated in the beam plane to accommodate the steering range of $\pm$ 12 degrees from the square waveguide, see fig. 3. Active cooling is foreseen for these mirrors, and they will be bolted or welded to the port plug structure. Focusing is optimized in the plane orthogonal to the beam plane for a spot size 2.1 meters from the mirror. Focusing in the beam steering plane is more difficult because the incident beam from the square waveguide moves over the mirror surface. If there is focusing in the beam steering plane this reduces the effective steering range. Therefore focusing of the beam is a tradeoff between steering range and spot size [7,8].
5. Two beams on one end mirror
A further optimization was identified by having two beams falling on one mirror, see fig. 4. This enables to increase the distance between the square waveguide and the end-mirror, from 300 to 350 mm for the upper row and from 250 to 300 mm for the lower, compared to the reference design. This, in turn, allows having wider beams on the mirror and therefore this decreases the beam radii substantially at the relevant plasma surfaces. Furthermore, a lower peak power density on the mirror can be achieved, allowing for relaxed cooling requirements.

6. Dog-leg option
The latest optimization of the remote-steering set-up has resulted in the dog-leg option. Here, the front mirror is replaced by a set of 2 mirrors. The set-up is arranged in such a way that 2 beams (one from the upper row and one from the lower row) use a common first front mirror (M1, on top, see fig. 5) and also a common second front mirror (M2, the lower one). In this way Din (the distance between the output of the square waveguide and the first front mirror) could be increased substantially to as much as 900 mm [9]. An important improvement of this set-up is a substantial reduction in the power density on the front mirrors. Now a value substantially below a maximum peak level of 10 MW/m² could be achieved. The exact value depends on further optimizations. An important issue is the possibility to avoid an overlap of the two beams on the same mirror for all the angles that are required for sending the beams to each location.

Another optimization criterion is, of course, the beam size in the plasma at the point of absorption of the mm waves. In this set-up, the beams that are directed to the plasma have a much lower Z position, leading to relative better NTM stabilization performances. The mechanical lay-out has undergone quite a number of improvements. The construction is much more robust now, e.g., all the former clashes with the port-plug sidewalls could be avoided now. The steering plane can be vertical now (see chapter 3) allowing easier access to the isolation valves, diamond windows and steering mechanisms. Furthermore, the opening required into the first wall panel is reduced to the smallest area that can be achieved for all RS launcher variants, the required cut into the neighboring lower regular blanket module is practically negligible.
7. **Shielding**

The neutron shielding provided by the port plug has several important tasks. The first task is the protection of the port connection weld to the vessel. Too much radiation will result in an unallowable high helium production in the stainless steel in that area, welding might become a problem than. The shielding capacity of the port plug is also important in order to provide a proper shielding for the CVD diamond windows located in the port plug inter-space and mini duct (see fig. 6), roughly 6 meters from the ITER plasma. The shielding capacity of the port plug is designed to be sufficient for having hands-on maintenance at the steering mechanisms, diamond windows and isolation valves during shutdowns. The acceptable radiation level for human access in the mini duct is expected to be reached after a few days [3,5].

8. **Safety aspects**

The ECRH RS launching system has two tritium boundaries under all conditions. The first boundary is the torus window, which can be shut off by an isolation valve. The secondary vacuum containment “the mini duct” (see fig.6) is the second tritium boundary. The mini duct can be shut off by a second valve, which is placed in the transmission line to the gyrotron.

Two important destructive events can occur during ITER operation. The first event is an explosion caused by a water leakage; this will result in a shock wave of approximately 2 bar. The diamond windows will be designed such that they can withstand such a pressure. The second event is a Hydrogen Detonation Event (HDE), this event results in a pressure wave of possibly 30 bars. In the case of an HDE, all windows will be blown out. The mini duct with a volume of approximately 8 m³ will function as an expansion vessel and the shock wave will be reduced, this will protect the transmission lines and the gyrotron window. The isolation valves mounted between the window and the torus are too slow to protect the torus windows in case of an HDE. The second valve in the transmission line might be in time to shut of the mini duct in order to reduce contamination of the transmission lines. The mini duct also will protect the port cell against contamination in case of an HDE or an explosion.

9. **Maintenance**

One of the major features of the ECRH RS launching system is the possibility to do hands-on maintenance. All sensible mm-wave components are located in the secondary vacuum containment “the mini duct”. By removing the mini-duct door, all steering components will come out of the port-duct and can be placed in an area of the ITER upper floor were radiation is more moderate, see fig.6. Checking, repairing and exchanging steering components will be taken into account during the
design process. Further it should be mentioned that for having maintenance on the mm-wave system the blanket cooling system and the torus vacuum remain unaffected.

Different types of handling devices are under development for clearing the port-cell of all the ECRH components in case a port plug has to be removed. All devices will be placed on air pads in order to ensure a smooth movement. The handing devices can be used for the transportation of the components to the hot cell, and used in the hot cell area as well, see fig. 7 [10].

Seen from the prospective of waste processing, the RS launcher system has also advantages. If something fails on a launching system it will be most likely the steering system. The steering systems of the RS system will have a low activation level. And therefore cheap to store or dismantle.

10. First low-power measurements.
A full-scale model of the entire mm-wave part of the proposed ITER ECRH upper-port launcher has been designed in all details. All components have been procured and assembled at the FOM institute. In figure 8 the following elements can be identified. On the top left side a taper transforms the small rectangular waveguide size of the low-power source into the “standard” ITER circular waveguide size of 63.5 mm. Following the taper some corrugated circular waveguides can be identified, amongst them two miter bends. These miter bends can be used in two configurations. Either grooved plates are included to allow for an elliptical polarization of arbitrary orientation and ellipticity. Or flat, water-cooled plates can be incorporated that can handle a power of 2.2 MW for cw operation for future long-pulse testing purposes.
From here, the mm-wave beam enters the vacuum vessel, where the mirror-steering mechanism is located, see chapter 3. Here, the beam falls first on the fixed focusing mirror and then on the movable plain mirror. From here the beam goes through the diamond window and the isolation valve into the square corrugated waveguide under the chosen angle between + 12° and - 12°. At the end of the 4.4 m long square waveguide the beam continues through another vacuum window under the same (but opposite) angle. Here an x-y-z scanner is located that measures the beam at a number of frequencies at each position. A full overview of the low-power measurements performed in Nieuwegein is given in [7]. An example is given in figure 9, where a measurement is performed at a scanning angle of 12°.

![Figure 9](image1.png)

**Figure 9.** Low-power measurement at a scanning angle of 12°. Measurement performed at a distance of 500 mm from the end of the square corrugated waveguide

Although, the beam shows a very nice sharp beam in the proper direction, also a small fraction of the power (less then 1 %) is going into other directions, clearly seen on the picture because of the very high dynamic range (> 100 dB) of the measuring device. A second measurement shows (in fig. 10) the propagating under -6° in the horizontal plane at a distance between 0 and 900 mm from the exit of the square corrugated waveguide. In June 2005 the entire set-up is transported to FZK at Karlsruhe, Germany where the system will be connected to a high-power (~ 1 MW) gyrotron in order to perform tests at ITER-relevant power levels, see fig. 11. These tests will be very close to the ITER conditions, at a frequency of 170 GHz, evacuated system, diamond window included in the test set-up. These tests can also be seen as a next step after very promising high-power tests in Greifswald [11] and Naka [12]. An interesting study on the alternative Front-Steering design is described in [13,14].

![Figure 10](image2.png)

**Figure 10.** Low-power measurement at a scanning angle of -6°. Measurement performed in a horizontal plane.
11. Conclusions
The design analyses and the detailed design of the mm-wave layout of the remote-steering concept for the upper-port launcher have demonstrated the feasibility of the remote-steering approach in the ITER environment. Furthermore, a full-scale mock-up line has been designed and built for testing at the appropriate ITER frequency and power level.

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