Integration of a dog-leg beam routing for the remote steering upper port launcher for ITER

D M S Ronden¹, W Bongers¹, A Bruschi², B S Q Elzendoorn¹, M F Graswinckel¹, B Lamers¹, A Moro¹, E Poli³, A G A Verhoeven¹

¹ FOM-Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, P.O. Box 1207, 3430 BE, Nieuwegein, The Netherlands
² Instituto di Fisica del Plasma, Association EURATOM-ENEA-CNR, via Cozzi 53, 20125 Milano, Italy
³ Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany

E-mail: d.m.s.ronden@rijnh.nl

Abstract. In the course of the development of a remote steering ECRH upper port launcher for ITER, it became clear that a modification could be introduced in the conceptual design in order to solve a number of structural weaknesses. Up to that point, all conceptual layouts were based on each remote steering beamline having a single front mirror placed in front of the square waveguide to aim the beam towards its resonance surface in the plasma. By placing an additional mirror per line inside the front shield of the upper port plug – effectively creating a dogleg routing – a number of structural issues were solved. This modification allows for a decrease of the heat load on the front mirrors and a shift downwards of the launching point. Additionally, through correct placement and focusing of the mirrors, the front shield penetration could be reduced by a factor of 4 and the cut in the blanket module below the upper port could be reduced significantly, while the level of overall performance could be increased as well. In order to visualise this new concept accurately, a more detailed design of the beam propagation was required. Through concerted effort within our institute, two different approaches were made to come to this new design; further advancements of the 3D-model and an Excel-based 2D simulation. This dual approach, together with beam tracing calculations done by affiliated institutes have indicated that the dogleg can prove to be a reliable design for a RS upper port launcher.

1. Introduction

In the course of the development of a remote steering ECRH upper port launcher [1] it has become clear that a number of key structural issues have remained unsolved. The main cause of this is the limited steering range of a remote steered beam when led through a square waveguide [2]. It has been found that at steering angles above +/-12 degrees, disturbances of the beam and losses inside the square waveguide rise sharply. Furthermore, CVD diamond windows [3], which form the primary vacuum boundary between the Tokamak vacuum vessel and the secondary vacuum, are available with a maximum aperture of approximately 95 mm. Since the diamond window is not placed directly at the entrance of the square waveguide (see figure 1), the beam has limited steering capability due to this as well.
The performance of the launcher is determined mainly by the maximum power density of the mmw-beam that can be achieved in the beam at its target in the plasma. The front mirror, if optimized for the smallest spot in the plasma, would have a focal distance small enough to completely eliminate the available scanning range of the beam as it exits the square waveguide. It can be concluded that the required scanning range and the power density in the plasma are conflicting demands, for which a compromise should be found.

The front mirror in itself has also shown to be a very critical component. Due to the inclination of the upper port, relative to the location of the target in the plasma, the incidence angle of the beam on the front mirror can be up to 70 degrees. Together with the steering capability of the incoming beam, this results in a large required size for the front mirror, relative to the space available in the upper port. These large mirrors have proven to be difficult to place inside the blanket shield module (BSM) [4] at the plasma-facing end of the upper port plug. Another effect of the large angle of incidence is a large variation in the distance between the square waveguide exit and the front mirror surface, which can be up to a factor 2.5 between +12 and –12 degrees steering. This in turn leads to a variation in its focal distance of the same order. Perhaps the biggest issue of designing the front mirrors is the peak power load to which the mirrors are subjected, resulting from losses of the mmw-beams. Each reflection of such a beam on a mirror leads to a marginal loss in the form of heat, which needs to be cooled away. The exact fraction (in the order of 0.3-0.5%) depends on parameters such as angle of incidence, surface roughness and possible depositions on the mirror surface. A design goal of 10MW/m² was determined as the maximum allowable peak power density in the spot on the mirror.

As a result of the above-mentioned issues, many different launcher options have been proposed in an attempt to solve them. The next chapter will briefly discuss some of these proposed designs.

2. Initial design philosophy
At the start of development of the RS ECRH upper port launching system, there were 3 ports available for a total of 24 transmission lines. The 8 lines that therefore needed to be fitted into each port required a complex orientation. This was caused by the fact that for the RS principle to work, the dimensions of the square waveguides need to comply with strict criteria [5]. This type of waveguide that transmits the mmw-beams from the steerable mirror inside the port duct towards the front mirrors in the BSM, have inner dimensions that are proportional to its total length ($L_{opt}$), according to:

$$L_{opt} = \frac{4a^2}{\lambda}$$  \hspace{1cm} (1)

With $a$ = inner width / height of waveguide; $\lambda$ = wavelength of mmw-beam. In the current design, $a = 44$ mm.
Since miter-bends can potentially cause considerable localized heating it was decided to not use these if possible. The resulting straight lines have limited freedom to be positioned inside the upper port and therefore the orientation of components in the front, directly influences the orientation of components in the rear.

The routing that came out of all the different design criteria, consisted of two rows of four fixed mirrors at the front, plasma facing end and four rows of two steerable mirrors at the rear end of the plug (see figure 2). This proposal was littered with problems that proved difficult to solve. First and foremost, the peak power density on the front mirrors of this design was calculated to be up to $15 \text{MW/m}^2$. Such a high density requires special measures such as a hypervapotron layout to be cooled away. Due to the challenging nature of such a layout it was preferred to try and limit the peak power density by increasing the spot size on the front mirrors. Another pressing issue with this layout was that the amount of space needed to fit these 8 lines was very limited. Since a larger spot on the front mirrors would also result in larger front mirrors and because the already apparent collisions within this design were never completely resolved, another approach needed to be investigated.

One way to increase the spot size on the front mirrors – as was mentioned in chapter 1 – is to use a property of a quasi optical beam; its increasing radius as a function of the distance from the exit of the waveguide. By increasing the distance between the square waveguide and the front mirror ($D_o$), the spot size on the mirror will increase accordingly. The order of change that was required to get the peak power density down to acceptable values was an increase of the $D_o$ from 250-300 mm to 400-500 mm. To create enough space to allow for this, it was attempted to limit the front mirror size by partly overlapping the beams in pairs and to then merge two front mirrors into one (See figure 3&4). Since the angle of inclination on the mirrors could hardly be changed, all these mirrors remained long. As a result, the heat load remained the same and little could be improved structurally.

**Figure 2.** An overview of the layout of the 8-beamline RS launcher
At this point it became clear that a potential fourth upper port could be used for ECRH. This meant that the amount of waveguides through each port could be reduced to 6. The designs that followed were an attempt to best make use of the extra space that became available. This led to yet another number of launcher concepts. The first was a design that is quite similar to the first 8-beam launcher, with 2 beamlines removed (see figure 5&6). It turned out that this option left little room to increase the $D_m$ to acceptable values.

The final design based on a single front mirror per line was also based on aiming more than one beam on each front mirror. This option had two front mirrors; one for the upper and one for the lower row of beamlines. This meant that each mirror reflected a total of 3 beams. The philosophy was to get two mirrors that were narrow enough to be placed side by side. It
turned out that this could not be achieved; the two rows remained located one on top of the other. Therefore also the $D_{in}$ could not be increased any further then the ‘regular’ 6-beamline option.

Another method that was proposed to increase the spot on the front mirrors was to use tapered waveguides; a square shaped entrance that remained the same dimension in the scanning direction, but widened along the perpendicular direction. The exit would then have a rectangular shape. The spot at the exit would have an elliptically elongated shape with an equivalent lower peak power density. Up to a certain distance from the exit of the square corrugated waveguide, this would result in a larger spot on the front mirror. The advantage of this approach is limited because an increase in beam waist at the waveguide exit also decreases the beam divergence.

3. A new approach

As an answer to many of the engineering issues, the principle of a dogleg routing was investigated. This routing is based on using two mirrors per beamline in a periscope-like arrangement. It was thought that with a correct refinement of all the parameters – nominal distances between the mirrors and waveguides, focal distances and angles of inclination – such a complex arrangement of components could be placed inside the BSM and thereby open an entire new range of possibilities for the RS upper port launcher. It turned out that to accurately model this arrangement, a highly parameterized model of each beamline had to be developed. This subject will be thoroughly discussed in the next chapter.

The first concept for a dogleg routing consisted of a layout with a total of 9 mirrors inside the BSM: 3 combined (M1) front mirrors for all 6 beamlines and 6 separate (M2) mirrors placed in the lower part of the upper port plug (see figure 7). Combining the M1 mirrors led to an overall reduction of the total mirror surface area and was necessary to save space for the lower set of mirrors.

As the initial dogleg design was checked in more detail, it turned out that this design could not entirely fulfill the desired requirements. The heat load on the front mirrors had reduced, but was still high. Also, the initial scanning range in the plasma was too small and could not be increased by further optimization of the parameters. The next step that did allow for this was combining the pairs of upper and lower M2 mirrors (see figure 8). This measure allowed...
for more space to be saved so that the $D_m$ of the M1 mirror could be increased by almost a factor 2, to an average of 700 mm. The resulting heat load on the front mirrors lays around 5 MW/m² per beam. The orientation of the components at the rear end of this dogleg layout is very similar to the previously mentioned dogleg layout. Figure 9 shows the general placement of the components for all dogleg options developed so far.

There turned out to be a number of major advantages of a dogleg routing, compared to the single-front-mirror options. First of all, since the beta angle of the mmw beams that are aimed at the plasma can be determined by the M2 mirrors only, it is no longer needed to rotate the waveguides along their central axis. This reduces the complexity of orienting the components at the rear end considerably, since the scanning plane can be kept vertical. Another advantage is the considerable reduction of the size of the required penetration in the front panel of the BSM. The relatively short focal length of the two front mirrors enables this by reducing the total occupied space of the steered beam. Since the beam cross section is smallest at the approximate location of the front panel penetration, the latter can be significantly reduced in size (0.24 m² for single end mirror options to 0.06 m² for the dogleg), thereby improving neutron shielding. The required cut in the lower blanket module could also be reduced from over 7 to about 0.5 dm³. Furthermore, the overall launching point is located lower than previously could be achieved. This results in an increase in performance, since the power is deposited at a smaller angle of incidence relative to the resonance surfaces.
3.1. Specifications of the dogleg launcher

The main parameters of the dogleg layout with combined M1 and M2 can be found in table 1.

| Parameter                                                   | Upper row | Lower row |
|-------------------------------------------------------------|-----------|-----------|
| Incoming scanning range [deg]                              | 12        |           |
| Nominal distance between square waveguide and M1 [mm]      | 700       | 700       |
| Size of M1 [mm]                                            | 100 \* 500|           |
| Nominal distance between M1 and M2 [mm]                   | 642       | 590       |
| Size of M2 [mm]                                            | 110 \* 570|           |
| Nominal $\alpha$ [deg]                                     | 51.5      | 47.5      |
| Nominal $\beta$ [deg]                                      | 17.9      | 19.6      |
| Scanning range in plasma [deg]                             | 40        | 36        |
| Location of virtual rotation points [mm]                   | (6530, 3874) | (6451, 3890) |

Table 1. Main parameters of the dogleg layout with combined M1 and M2 mirrors

In the above table, `$\alpha$` describes the angle between the outgoing beam centerline and the equatorial plane of the ITER vessel and `$\beta$` describes the angle between the outgoing beam centerline and its poloidal component. The locations of the virtual rotation points are expressed by a set of (R,Z) coordinates, relative to the ITER axis system.

Combining the M1 and M2 mirrors has resulted in the upper and lower row not having the exact same range in the plasma. This is caused by the fact that the exits of the square waveguides of both rows are not at the same location, nor point in the same direction. The required range (which can best be described by a set of R,Z values: Z = 1900-3400 at R = 5650 [mm]) should be covered by both rows, so this means there is a slight over span of both rows on either side of the required scanning range, as is illustrated in figure 10.

![Figure 10. The effect of combining the mirrors for the upper and lower row of the dogleg layout](image)

The 3D model that was developed for calculating the beam propagation has provided a moderately accurate estimation of the launcher’s performance. Mainly the relative comparison – between different launcher options – has shown to be of considerable value. It was heavily relied upon to try to increase the performance of the dogleg. This work is still
ongoing. Table 2 shows the spot sizes and the locations of the spots under certain steering angles for the dogleg layout.

| Local steering angle | Spot radius [mm] | Z-position [mm] |
|----------------------|------------------|-----------------|
|                      | Perpendicular    | Vertical        |
| Upper row            |                  |                 |
| 12°                  | 45               | 53              | 3304 |
| 6°                   | 87               | 66              | 3080 |
| 0°                   | 93               | 143             | 2794 |
| -6°                  | 135              | 273             | 2292 |
| -8.5°                | 179              | 436             | 1898 |
| -12°                 | 304              | 1129            | 775  |
| Lower row            |                  |                 |
|                      | Perpendicular    | Vertical        |
| Local steering angle |                  |                 |
| 12°                  | 43               | 50              | 3422 |
| 8°                   | 54               | 66              | 3301 |
| 6°                   | 56               | 71              | 3240 |
| 0°                   | 73               | 107             | 3030 |
| -6°                  | 98               | 174             | 2702 |
| -12°                 | 175              | 463             | 1900 |

Table 2. Spot sizes of the dogleg, measured using Catia

In the above table, the spot sizes are measured in two directions: the perpendicular radius is measured in a plane perpendicular to the direction of propagation, while the vertical radius is measured in a plane tangential to the plane that represents the absorption area on the resonance surfaces in the plasma – as mentioned in paragraph 3.1: Z = 1900-3400mm at R = 5650mm, relative to the ITER global axis system.

4. Parameterized design of the beam propagation

Parallel to the mechanical design, the beam propagation for different conceptual designs has regularly been checked through detailed beam tracing calculations [6, 7]. This has resulted in a routine of exporting the beam parameters from the structural model as soon as a new conceptual design was developed and let these be analysed through beam tracing. This is a necessary, but time-consuming feedback loop that complicates the routine of proposing new beamline layouts. In order to make this phase less time-consuming, effort was put into designing a structural model that would by itself be accurate enough to already indicate feasibility, before a first detailed beam trace was performed. This was done with the aid of parameters.

The use of parameters allows the mechanical designer to insert quasi-optical formulae [8] that calculate the beam propagation as a function of input parameters that control the mirror locations and shapes. The big advantage of such an approach is that the components can be located and aligned very accurately so that instant feedback is provided to determine possible collisions.

The 3D model that was developed forms an expansion of an existing 2D model that was created in Excel. The methodology of calculation is similar, and therefore these two models act as a reliable confirmation when results are compared. All relevant effects of beam propagation were included in the calculation. These include the shift of the beam waist location, which occurs as a result of the variable length of the beam path as a function of the steering angle and the shift of the launching point as a result of the variable optimum length of the square waveguide as a function of the steering angle ($\phi_h$). This last effect can be described by expanding the following expression compared to (1):

$$L_{opt} = \frac{4a^2}{\lambda} * \frac{1}{1 + \frac{1}{2} \sin^2 (\phi_h)}$$  \hspace{1cm} (2)

These effects can have a considerable influence (~10%) on the beam radius and are therefore important to take into account.
References

[1] ITER Design Description Document G52 DDD 5 01-05-29 W0.1 (2003) 5.2, “Electron Cyclotron Heating and Current Drive System”, § 1
Verhoeven T, Elzendoorn B, Bongers W, Bruschi A, Cirant S, Danilov I, Fernandez A, Gantenbein G, Graswinckel M, Heidinger R, “Design of the Remote Steerable ECRH launching system for the ITER upper ports”, IAEA Technical Meeting on ECRH Physics and Technology for ITER, May 2-4, 2005, Societa’ del Casino, Como, Italy
Graswinckel M, Bongers W, Fernandez Curto A, Elzendoorn B, Kruyt O, Lamers B, Ronden D, Ruigebregt M and Verhoeven T, “Low power measurements on a remote steering upper port launcher mockup for iter”, IAEA Technical Meeting on ECRH Physics and Technology for ITER, May 2-4, 2005, Societa’ del Casino, Como, Italy
Henderson M, Chavan R, Heidinger R, Nikkola P, Ramponi G, Saibene G, Sanchez F, Sauter O, Serikov A, Zohm H, "The front Steering launcher Design for the ITER ECRH Upper Port", IAEA Technical Meeting on ECRH Physics and Technology for ITER, May 2-4, 2005, Societa’ del Casino, Como, Italy
Chavan R, Henderson M A, Sanchez F 2005 "A Frictionless Steering Mechanism for the Front Steering ECCD ITER Upper Port Launcher", IAEA Technical Meeting on ECRH Physics and Technology for ITER, May 2-4, 2005, Societa’ del Casino, Como, Italy

[2] Kasparek W, Gantenbein G, Plaum B, Wacker R, Chirkov A, Denisov G, Kuzikov S, Ohkubo K, Hollmann F, Wagner D, “Performance of a remote steering antenna for ecrh/eccd applications in iter using a four-wall corrugated square waveguide” Nucl. Fusion 43 (2003), 1505 - 1512

[3] Danilov I, Heidinger R, Meier A and Spaeh P, “Torus window development for the iter ecrh upper launcher”, IAEA Technical Meeting on ECRH Physics and Technology for ITER, May 2-4, 2005, Societa’ del Casino, Como, Italy

[4] Heidinger R, Fischer U, Hailfinger G, Henderson M, Kleefeldt K, Saibene G, Serikov A, Spaeh P, Verhoeven T, “Structural integration studies for the ITER ECRH Upper Launcher”, IAEA Technical Meeting on ECRH Physics and Technology for ITER, May 2-4, 2005, Societa’ del Casino, Como, Italy

[5] Moeller C, "A method of remotely steering a microwave beam launched from a highly overmoded corrugated waveguide“, Proceedings of the 23rd Int. Conf. on Infrared and Millimeter waves, Colchester 1998, eds. T.J. Parker and S.R.P. Smith, ISBN 0-9533839, 116-118 (1998).

[6] Bruschi A, Cirant S, Moro A and Sozzi C, “Advanced optics for remote steering iter ecrh upper launcher”, IAEA Technical Meeting on ECRH Physics and Technology for ITER, May 2-4, 2005, Societa’ del Casino, Como, Italy

[7] Zohm H, Heidinger R, Henderson M, Poli E, Ramponi G, Saibene G, Verhoeven T, "Comparison of the performance of different options for the ITER ECRH Upper Launcher", IAEA Technical Meeting on ECRH Physics and Technology for ITER, May 2-4, 2005, Societa’ del Casino, Como, Italy

[8] Goldsmith P. "Quasi Optical Systems", New York, IEEE Press, § 2, (1998)