Low power measurements on a remote steering upper port launcher mock-up for ITER

M F Graswinckel¹, W A Bongers¹, Á Fernández Curto², B S Q Elzendoorn¹, O Kruyt¹, B Lamers¹, D M S Ronden¹, M R Rugebregt¹, and A G A Verhoeven¹

¹FOM Institute for Plasma Physics “Rijnhuizen”, Association EURATOM-FOM, Edisonbaan 14, P.O. Box 1207, 3430 BE Nieuwegein, the Netherlands
²Laboratorio Nacional de Fusión, Asociación EURATOM-CIEMAT, 28040 Madrid, Spain

graswin@rijnh.nl

Abstract. The association FOM-Rijnhuizen is developing a plug-in 170 GHz ECW launcher system for use in the upper-ports of ITER, based on the remote steering (RS) principle. The launching system enables up to eight mm-wave beams per port plug to be directed from the feeding waveguides through corrugated square waveguides (≈ 44x44 mm²) inside the port plug to the plasma. A mock-up system has been manufactured, capable of vacuum & high-power short-pulse operation. The transmission line consists of a taper, to launch an HE₁₁ mode in 63.5 mm circular corrugated waveguide. The circular waveguide is used as input for the steering mechanism, housed in a vacuum vessel, which directs the beam under an angle between -12˚ and 12˚ into the copper square corrugated waveguide. Antenna patterns from the exit aperture of the square waveguide are scanned using a 3-axis scanner.

1. Introduction

Several high power tests on remote steering waveguides were performed at different institutes, for example by Stuttgart University [1], and JAERI [2]. Good results were obtained using IR-camera measurements. From these measurements it was shown that a usable range for remote steering is about -12 to 12 degrees. The low power measurements in this paper are on a waveguide that has a closer waveguide dimension, operating frequency, length and steering mechanism to what is foreseen for ITER. These low-power measurements are a preparatory phase for high-power tests, scheduled to be performed in FZK, starting July 2005. Waveguide performance will be inferred from antenna pattern measurements. What are of interest are slight differences in beam parameters (angle, waist etc.) relative to the input beam.

In the current design (FOM, see for example [3] & [4]) for the upper port launchers for ITER, the square corrugated waveguide (SCW) is 4321 mm in length and has a 44 mm² aperture. The waveguide under test here was supplied by General Atomics (GA), and is vacuum-tight, so that only the inner part of the waveguide need be evacuated for high power operation. Additionally, this enables easy access to the waveguide outer surface with thermocouples and the infrared camera. For ITER, this vacuum tightness of the waveguide itself is not a requirement. The waveguide was ordered slightly longer than 4321 mm, namely 4389 mm, so that after the measurements, it can be cut to its optimum length, which could be different from 4321 mm. It was planned to measure the differences between different methods of input steering (by changing the relation between input angle & location...
steering at large angles can be improved. However, due to a shift in time-schedules, only the cam-profile which injects the beam exactly in the centre of the waveguide aperture was used.

2. Measurement setup

The measurement setup consists of a standard 0-20 GHz Agilent VNA (Vector Network Analyzer) and uses a custom system designed by ELVA to allow measurements in a range from 167 – 173 GHz. To couple power from the network analyzer into the 63.5 mm waveguides, a taper is used, tapering from D-band to 63.5 mm corrugated waveguide. The tapers length is 842 mm and it has mode purity at its output better than 99.5%. Connected to the taper is a section consisting of corrugated circular waveguide and two mitre bends. The two mitre bends have interchangeable polarizing or flat mirrors. The polarizing mitre bends will be used in the high power setup (where a section of the transmission line will be inclined 45˚), to have a horizontal, vertical or 45˚ polarization angle alpha. The corrugated waveguide then enters a vacuum vessel, which houses the steering mechanism, the gate valve (vacuum boundary), and the diamond window. The test results presented here were performed with only the steering mechanism installed in the vacuum vessel. The steering mechanism launches the mm-wave beam into the waveguide with an angle between -12 and 12˚.

Figure 1: Measurement setup

As the steered beam radiates from the open ended waveguide aperture (seen in Figure 1), the field is scanned using a three-axis (x-y-z) scanner on which the receivers are mounted. There are two receivers on the scanner so that both horizontal and vertical polarization can be measured simultaneously.
3. Steering mechanism

The steering mechanism focuses the incoming beam from the circular corrugated waveguide \((w_0 = 20.32 \text{ mm})\) with an ellipsoidal mirror to about 20 mm in front of the waveguide input. Here, care should be taken that not too much power of the input beam falls onto the edges of the corrugated waveguide. This power is unwanted at this location and creates additional diffraction losses. Coupling losses in this section could be 2%.

\[
\begin{align*}
&d_1 = 230 \\
&d_{in} = 100 \\
&M1 \\
&M2 \\
&d_{out} = 100
\end{align*}
\]

Figure 2: In the steering mechanism, a positive steering angle is moving mirror M2 closer to M1. The combined translation rotation of the (flat) steering mirror M2 is effected by a ball bearing roller, attached to M2 and rolling over a profiled support (cam profile). In this configuration, the combined movement can be done using only one actuator. Additionally it has the advantage that almost any kinematics function can be achieved by simply replacing the cam profile.

| Symbol | Value | Units |
|--------|-------|-------|
| Input waist at circular waveguide aperture | \(w_m\) | 20.32 | mm |
| Distance from circular waveguide to mirror M1 | \(D_{in}\) | 100 | mm |
| Nominal Distance from SCW to mirror M2 | \(d_1\) | 230 | mm |
| Nominal distance from M1 to M2 | \(d_2\) | 170 | mm |
| M1 focal distance | \(f\) | 538 | mm |
| M1 output waist size | \(w_0\) | 12.77 | mm |
| M1 output waist distance | \(d_{out}\) | 365.02 | mm |

Table 1: Steering mechanism parameters

The quality of the output beam depends partly on the input steering mechanism, namely on the relation between the angle of injection and the injection point on the waveguide aperture. To optimize the output beam the cam profile, inside the steering mechanism can be changed to alter the relation between the mirror position, and the steering angle.

From the parameters in Table 1, the input beam parameters can be calculated, giving Figure 3.
As can be seen in Figure 3b, the beam waist shifts slightly (20 mm) into the SCW at large positive steering angles. Due to a shift in the time-schedule, all measurements were done with the cam profile that does not have this compensation.

An effort is undertaken, to increase the performance of the steering mechanism by examining the possibility of having imaging optics. This would eliminate the 2% mode conversion loss from HE_{11} waveguide mode to TEM_{00} free space Gaussian beam.

4. Measurement results

The parameters of interest from the measurements are mainly the origin of the beam, the beam size in both planes, and the Gaussian content. Especially the Gaussian content is important to have good operation of a remote steering launcher.

We measure plane scans; scans in a plane perpendicular to the waveguide axis, at a distance of 500 mm from the aperture. The scanned area is 800x200 mm$^2$.

Since for low power measurements, each plane scan at a usable resolution takes a long time (half a day or so with our current setup, for 31 frequencies), not too many intermediate angles were examined. The alternative to doing full plane scans is performing simply line scans, in the horizontal or vertical plane. Although line scans yield less information compared to full pattern scans, they still are useful since side lobes appear mainly in the direction of steering. This is also the scanning direction of the measurement.
Figure 4 (a-e): On the left, are shown the resulting power distributions (a.u.) for steering angles of +12, +6, 0, -6, and -12, top-down respectively. Already at the extreme steering angles, significant side lobes are appearing at a level of about -16 dB for -12 degrees steering angle. These measurements were performed with E in the plane of steering, which is the worst case scenario. The +12 degrees case is not simply the mirror image of -12, this is due to differences in path length in the input steering mechanism.

Figure 5 (a-e): In the linear domain (a.u. of power) the side lobes are much less pronounced. Only at -12 degrees steering angle the anti-symmetric lobe becomes slightly visible. In the linear domain, the pictures are directly comparable to measurements done using an infrared camera on an absorbing screen. Typically IR-camera measurements yield relatively poor dynamic range compared to low power measurements.
To have a more quantitative analysis, the Gaussian content of the beam is examined. The process will be described here. Allowing the beam size in two planes ($w_x$ & $w_y$) and its offset centre position ($x_0$, $y_0$) to be free parameters; the following equation is minimized using a numeric downhill simplex method, readily available in the MATLAB function `fminsearch`.

$$\text{goal} = 1 - c_m^2 \quad (1.1)$$

With $c_m$ defined as:

$$c_m = \frac{\int_{A} E_m f dA}{\sqrt{\int_{A} E_m^* f dA \int_{A} f^* dA}} \quad (1.2)$$

Where $E_m$ is the 2D electric field distribution of a fundamental mode hermite-gaussian beam and $f$ is the measured field (which is proportional to the square root of the measured power).

Since every scan is made using a network analyzer, the antenna pattern is available in the datasets for a range of frequencies, usually some 31 steps, between 167 and 173 GHz. An automated analysis for the Gaussian content over the entire range of frequencies can be used to find the optimum frequency of operation this results in the following graph, from which the optimum frequency can be found.

![Frequency dependent Gaussian content of the waveguide](image)

From Figure 6, the frequency can be determined where the performance of the waveguide averaged over the measured angles is optimal. For this waveguide it is determined to be 171.54 GHz.

5. **Polarization measurements**

For transmission of arbitrary polarized beams through the SCW, it is required that the relative phase between modes in the waveguide (with E parallel to either the horizontal or vertical waveguide edge) is preserved. To determine if this is the case, a beam is launched into the waveguide with ($\alpha=45^\circ$, $\beta=0^\circ$) polarization. This is a linear polarisation, at an angle of 45° to both sides of the waveguide. If this beam is transmitted without depolarisation, the waveguide will support arbitrary input polarizations.
The polarisation of the beam radiating from the aperture of the waveguide is determined using a rotating probe, mounted on the scanner. The probe measures $E//\theta$ at different angles to the waveguide. From this both $\alpha$ and $\beta$ can be found.

As a test to find possible depolarisation, the steering mechanism was set at 12°, and the polarisation at this angle measured (perpendicular to the beam).

| Frequency (GHz) | $\alpha$ | $\beta$ |
|----------------|---------|---------|
| 167            | 47.0°   | 0°      |
| 170            | 47.0°   | 0°      |
| 171.5          | 46.9°   | 0°      |
| 172            | 46.7°   | 0°      |
| 172.5          | 47.2°   | 0°      |
| 173            | 47.1°   | 0°      |

Table 2 Measured polarisation angles as a function of frequency

Note that in our current setup, accurately determining beta is difficult, in Table 2, the accuracy in beta is about 10°, in the meantime, the accuracy has improved to about 2°, but the measurements have to be redone.

6. Conclusion

Already low power measurements, show that the antenna patterns at low power for an ITER-like waveguide are very much usable for application in a remote steering system, significant side lobe appear only at the extreme angles but are still manageable. Depolarisation of the waveguide needs further effort to find the maximum depolarisation, but first results are encouraging. Additional measurements will be performed to have a firm base for comparison with the high power measurements to be done at FZK. This work is supported by the European Communities under the contract of Association between EURATOM and FOM, with financial support from NWO. This work was carried out under the EFDA technology research programme activities, EFDA technology task TW3-TPHE-ECHULA and B1. The views and opinions expressed herein do not necessarily reflect those of the European Commission.
7. References

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

[2] K. Takahashi, C. P. Moeller, K. Sakamoto, K. Hayashi and T. Imai
High power experiments of remote steering launcher for electron cyclotron heating and current drive Fusion Engineering and Design, Volume 65, Issue 4, July 2003, Pages 589-598

[3] D.M.S. Runden, et al., “Integration of a dog-leg beam routing for the remote steering upper port launcher for ITER”, this conf.

[4] A.G.A. Verhoeven, et al., “Design of the Remote Steerable ECRH launching system for the ITER upper ports”, this conf.