High-power tests of a remote steering launcher mock-up at 140 GHz

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Abstract. This paper reports the results of the high-power test of a remote steering launcher mock-up at 140 GHz, which were performed at the ECRH installation for the future stellarator W7-X at IPP Greifswald. The mock-up test system consists of a 6.62 m long corrugated square waveguide with a steerable optic at the entrance and various diagnostics at the exit of the waveguide. A straight and a dog-leg version of the launcher were investigated.

The high-power tests of the straight setup have been performed with powers up to $P_0 = 700$ kW (typically 500 kW) and pulse lengths of up to 10 seconds.

For both polarizations (parallel and perpendicular to the steering plane), no arcing was observed in spite of the fact, that the experiments were performed under ambient atmospheric conditions. After the integration of 2 mitre bends in the setup, arcing limited the usable parameter range.

The ohmic loss $P_\Omega$ of the waveguide was measured via the temperature increase of the waveguide wall, and was used to calibrate the calculated angular dependence of the total ohmic losses of the waveguide. Short-pulse radiation pattern measurements with thermographic recording show high beam quality and confirm the steering range of $-12^\circ < \phi < 12^\circ$.

1. Introduction
The International Thermonuclear Experimental Reactor (ITER) will be equipped with a 170 GHz electron cyclotron resonance heating (ECRH) system which can be applied for very localised heating of the plasma or for current drive (ECCD) in the plasma \cite{1}. One major objective of this system is the suppression of plasma instabilities, in particular the so-called neoclassical tearing modes (NTMs), which are very likely to appear in current operating scenarios...
of ITER. The upper launcher concept under investigation, which is foreseen to fulfill this task, is the so-called remote-steering launcher.

The launcher basically consists of a corrugated square waveguide with a steerable mirror at the entrance of the guide [2]. Owing to the imaging properties of the guide [3], the steering at the input is transformed to the output of the waveguide if the length $L = 4a^2/\lambda$ where $a$ is the transversal dimension of the square waveguide and $\lambda$ is the free space wavelength. Thus, beam steering without movable parts near to the plasma is possible.

At present, the upper launcher is designed by a consortium of European research institutes [4], and various tests will be performed after manufacture of a prototype launcher. As an intermediate step, low-power [2] as well as high-power tests of a mock-up were performed.

This paper reports the results of the high-power test of a remote steering launcher mock-up at 140 GHz, which were performed using the ECRH installation for the future stellarator W7-X. For this device under construction at IPP Greifswald, a 140 GHz, 10 MW CW ECRH system is presently being installed [5]. Prototype gyrotrons were developed in Europe (Forschungszentrum Karlsruhe (FZK) in collaboration with several other research institutes and Thales Company as the industrial partner [6]) and USA (CPI). At IPP Greifswald, the first gyrotron “Maquette” became operational at the end of 2003 and is operated routinely with pulses up to 800 kW. This tube was used for the mock-up tests.

The millimetre waves are transmitted from the source to the plasma via quasi-optical transmission lines [7]. The mirrors and other components are placed in an underground duct connecting the gyrotron building with the stellarator hall. The RS-launcher mock-up experiments were performed in this underground duct, as it provides an ideal test bed for high-power experiments under atmospheric conditions.

2. Design of the beam-line mock-up for tests at 140 GHz

The basic experimental setup in the underground duct connecting the gyrotron hall and the W7-X hall is shown in Figs. 1-3.

For the tests of the upper launcher mock-up, the beam from the Maquette gyrotron is detoured in front of the dummy load by a fixed beam shaping mirror and a rotatable mirror and directed into the corrugated square waveguide as shown in Fig. 1. The aluminium waveguide with a cross-section of 60 $\times$ 60 mm and a length of 6.62 m is mounted on a stable frame construction. The beam shaping mirror is used to match the incident beam to the diameter of the square waveguide. The rotatable mirror is mounted on a remotely controlled turntable and determines the steering angle of the launcher. It is equipped with a polarization sensitive directional coupler to check the polarization of the input beam set by polarizers. The steering plane is horizontal.

At the entrance and the exit of the waveguide, arc detectors are installed. Near to the entrance of the waveguide, an array of thermal sensors is installed to measure temperatures in the waveguide. The opposite waveguide wall is coated with an IR absorbing surface to detect the surface temperature distribution of the waveguide (see Fig. 2). At the exit of the waveguide, a long-pulse calorimetric load from CNR/IFP Milano [8] (Fig. 3) is installed to dump and to measure the transmitted power for long-pulse experiments; alternatively, an absorbing screen can be set up to record the radiation pattern of the launcher with an infrared camera.

3. Characterization of the input beam

Prior to the experiments, the input beam to the experimental setup was characterized using thermographic techniques. This resulted in a beam waist of 17 mm and an average position of the waist of about 50 mm inside the waveguide. This small deviation from the design (waist position at the waveguide entrance) is negligible, as the Rayleigh-length of the beam of 424 mm is large compared to this offset.
As all tests were performed with parallel and perpendicular polarization with respect to the steering plane, the polarization of the input radiation as function of the polarizer settings was checked prior to the experiments using a polarization sensitive coupler integrated into the steering mirror. For both polarization planes, the tests yielded a linear polarized beam with a maximum cross-polarized component of 3%.

The positions and orientations of the steering mirror, the axis of the turn-table and the waveguide entrance had been chosen such that the beam enters the waveguide aperture in its centre for all steering angles. To confirm the input geometry, the beam position of the input beam was checked by thermographic recording of the beam with a target on the waveguide entrance. Within the measurement accuracy of about 3 mm, no significant deviation from the ideal beam position could be detected.

4. Temperature increase of the waveguide wall

4.1. Theory

The most simple approximation of the fields in the waveguide is the assumption of a Gaussian beam, which propagates along a zig-zag line in the waveguide. If one knows the absorption of a single reflection at the wall, the total losses and the heat load can be estimated by calculating the number of reflections from the steering angle and the waveguide dimensions.

A more precise calculation of the field structure involves the expansion of the incoming Gaussian field into hybrid modes of the corrugated waveguide [9]. Once the complex mode
amplitudes at the entrance of the waveguide are obtained, the modes can be propagated in the waveguide with known phase constants. A superposition of the mode fields allows the calculation of all field components at arbitrary waveguide positions.

For estimating the losses, the longitudinal component of the $H$-Field at the walls is of interest, because it corresponds to a wall current in transversal direction, which is the main cause of the loss. A calculated pattern of the transversal wall currents is shown in Fig. 4. One can see, that at the beginning, the beam looks nearly Gaussian. Further inside the waveguide however, the pattern no longer consists of distinct reflections due to the relative phase shift of the modes resulting from the different phase constants.

At the output, the input field is reconstructed antisymmetrically if the length is chosen properly. In this case the overall field pattern is approximately symmetrical to the transversal plane at $z = L/2$. This results in a last reflection near the end of the waveguide, which is again similar to a reflected Gaussian beam.

The estimation based on zig-zag propagation however, was found to be in reasonable agreement with the more precise calculation using the mode analysis method.

4.2. Setup for the temperature measurements
For measuring the temperature increase of the waveguide wall with an IR-camera, the outer wall was coated with black self-adhesive plastic foil to improve the radiation characteristics. On the opposite side, thermocouples were attached in holes of the wall to measure the temperature near the inner wall (see Fig. 2).

4.3. Heat distribution at the outer waveguide wall
The measurements were done with powers up to 700 kW and pulse lengths of up to 10 s. Fig. 5a shows the heat distribution at the outer waveguide wall for a steering angle of 11.6°, which is close to maximum angle of 12° up to which the antenna can be used. One can see the 2nd and 4th reflection of the beam. The trapezoidal deformation of the image was numerically compensated, the rectified image is shown in Fig. 5b. The calculated wall current density is shown in Fig. 5c. A direct comparison of Figures 5b and 5c is difficult because e.g. the exact location of the waveguide entrance cannot precisely determined from Fig. 5a. One can see however, that the locations of the maxima agree well.

4.4. Estimation of the absorption coefficient for one reflection
The temperature values near the inner waveguide wall, which were detected by the thermocouples, were used to extrapolate the power loss due to the first reflection of the beam at the waveguide wall.
The peak temperatures at the end of the pulse were used to calculate the thermal energy content in the waveguide wall. This was achieved by assuming Gaussian temperature profiles in both the transversal and longitudinal direction. This profile was fitted to the measured values (See Figs. 6 and 7).

Figure 6. Gaussian fit to the measured temperature profiles

In addition, the temperature was assumed to be constant from the inside to the outside of the wall, i.e. the thermal conductivity was assumed to be infinite in this direction. This assumption can be made since the gyrotron pulse was 10 s, while the heat diffusion time constant from the inner- to the outer wall is in the order of 0.25 s. Any cooling loss during the heating phase could also be neglected, since the temperature increases almost linear in this case.

The resulting heat distribution (See Fig. 7) could be used to calculate the heat content of the wall and thus the total heat power due to one reflection. For a steering angle of 11.6°, the resulting power losses for the first reflection are 0.9 kW (0.18 %) and 0.3 kW (0.06 %) for parallel and perpendicular polarization respectively for a gyrotron power of 500 kW. These values are in agreement with the results obtained from 3 mirror resonator measurements [10], where the absorption coefficient for one reflection could be fitted to $a_{\text{par}} = 0.0098 \sin \phi$ and $a_{\text{perp}} = 0.0030 \sin \phi$ for parallel and perpendicular polarization respectively. For a scanning angle of 11.6° degrees, the low-power fit results in $a_{\text{par}} = 0.197\%$ and $a_{\text{perp}} = 0.060\%$, which is in excellent agreement with the high power measurements.

4.5. Estimation of the total ohmic losses

The overall efficiency could not be measured directly, because there was no reliable possibility for monitoring the power at the input of the waveguide.

One can, however, calculate the wall current distribution at the inner waveguide walls (See Fig. 4). The wall current corresponds to the ohmic losses ($P_{\text{loss}} \propto I_{\text{wall}}^2$) but the
proportionality factor cannot easily be derived, because it depends on the complicated field
distribution inside the corrugation grooves. From the current distribution, however, one can
calculate the loss of the first reflection normalized to the total loss. For a steering angle of 11.6°,
this ratio is 0.0438. This results in total losses of 4.1 % for parallel polarization and 1.36 % for
perpendicular polarization.

From these results, the overall losses of the launcher for parallel and perpendicular
polarizations can be calculated. These can be estimated by the formulas:

\[ \frac{P_{\Omega,||}}{P_0} = 0.033 \phi^2[^\circ, \%] \]
\[ \frac{P_{\Omega,\perp}}{P_0} = 0.01 \phi^2[^\circ, \%]. \]

These formulas are derived from the data by integration of the wall currents over the side
walls of the waveguide under the assumption, that the contribution of the walls parallel to the
steering plane is negligible. Within the error bars, a good agreement between the low and high
power measurements is found.

5. Far-field measurements
The far-field measurements were carried out by placing an absorbing screen at a distance of
2.175 m from the waveguide output and recording the field pattern with an IR camera. Due
to the limited space, the distance of the screen from the waveguide output could not be freely
chosen. For safety reasons, a temperature rise of no more than 10°C (as shown by the camera)
was allowed. Even in this case, the local temperature increase can be higher, without being
detected due to the limited spatial resolution of the camera. The gyrotron was operated at a
power of about 250 kW, the pulse length was 0.3 ms. These parameters correspond to the lowest
possible pulse energy, at which the gyrotron operates reliably.

![Figure 8](image)

**Figure 8.** Far field patterns at a distance of 2.175 m from the waveguide output for parallel
(left) and perpendicular (right) polarization

Fig. 8 shows a summary of far-field patterns for both polarizations and all steering angles.
For steering angles up to 12°, the patterns look nearly identical. This indicates, that the antenna
can also be used for elliptically polarized beams, which are necessary for ECCD. At a steering
angle of 15°, the patterns for both polarizations differ slightly. This is due to the fact, that the
corrugation is not perfectly matched for 140 GHz resulting in slightly different phase constants
for higher-order modes. Earlier low-power experiments [2] showed, that the antenna with the
current corrugation profile is completely polarization independent at a frequency of 158 GHz.
6. Breakdown limits
Arc detectors were used at the input and output of the straight waveguide to explore the breakdown limit of the mock-up. For the setup without mitre bends, no limitation due to arcing in the square waveguide was found. In table 1, typical parameters of the shots performed are listed.

| \( t \) [s] | \( P \) [kW] | \( \phi \) [°] | Polarization | Remarks |
|------------|-----------|-------------|-------------|---------|
| 10         | 500       | 11.6        | Perp.       | Typical parameters for monitoring the temperature increase of the waveguide wall |
| 10         | 500       | 9.0         | Parallel    |         |
| 1          | 700       | 11.6        | Perp.       | Pulse length limited by gyrotron |
| 0.2        | 800       | 11.6        | Perp.       | Far-field measurement |
| 0.0003     | 250       | 20.0        | Parallel    |         |

Table 1. The parameter space (pulse length \( t \), power \( P \) and steering angle \( \phi \)) were the waveguide has been operated without observing a limitation due to arcing in the waveguide. The polarization is given with respect to the steering plane. For monitoring the temperature increase of the waveguide wall, the gyrotron has been operated in a reliable and reproducible regime. In the case of far-field measurements, the pulse length and power was reduced in order to avoid damaging of the absorber material.

7. Integration of mitre bends
7.1. Setup
For ITER, mitre bends are possibly needed in the remote steering antenna to reduce the neutron flux to the window. Therefore, the straight waveguide setup was modified by inserting two \( 90^\circ \) bends (3.1 m straight - \( 90^\circ \) bend - 0.28 m straight - \( 90^\circ \) bend - 3.24 m straight. Thus, the length of the complete waveguide run was 6.62 m, i.e., nearly identical to the straight setup. Input beam and steering system were kept unchanged.

7.2. Radiation patterns
Corresponding to the tests of the straight waveguide, radiation patterns were recorded by thermographic imaging.

Again, the system was tested with both polarizations. The radiation patterns show, that the steering range of \(-12^\circ < \phi < 12^\circ\) is identical to the straight launcher. However, side lobes opposite to the main beam with a level of -21 dB...-17 dB with respect of the main lobe can be seen. These side lobes are mainly the result of diffraction at the non-perfect wall of the mitre bends.

In order to get an estimate on the diffraction loss, the power in the main lobe was deduced from the thermographic images and related to the total radiated power within the field of view of the camera (See Fig. 9). Within the steering range, the efficiency is at least 86%. For the polarization perpendicular to the steering plane, no remarkable differences compared to the polarization parallel to the steering plane where found.

7.3. Long-pulse test, arcing problems
In contrast to the straight setup, arcing often occurred in the region of the mitre bends. For short pulses (typ. 1 ms), operation at power levels around 500 kW was possible in the polarization parallel to the steering plane. In the perpendicular polarization, arcing occurred earlier even for small angles. This can be explained by field enhancement at the sharp edges of the mitre
bends for the polarization perpendicular to these edges, i.e., perpendicular to the steering plane. Long-pulse experiments where performed at steering angles of $\phi = 0^\circ$ and $\phi = 10.8^\circ$ with powers of up to 500 kW and pulse lengths of up to 5 s. At $\phi = 0^\circ$, arc-free operation was possible at 500 kW in parallel polarization and up to about 300 kW in the perpendicular polarization. For $\phi \approx 10^\circ$, arc-free operation was difficult to achieve even with moderate power. Here, only periodic pulses (10 ms, duty cycle 0.5) could be transmitted. A summary of the arcing limits is given in Table 2. It should be noted, that determining precise arcing limits is not easy because after one arc, the air inside the waveguide is polluted which results in a lower breakdown field strength for subsequent pulses.

The temperature of the outer waveguide wall was also recorded with the infrared camera. While the temperature patterns near the waveguide entrance look similar to the straight waveguide (see Fig. 5), a strong heating of the wall was observed at the mitre bends. The peak temperature is approximately 3 times higher than the peak temperature at the location of the first reflection near the waveguide entrance.

This can be explained by the fact, that the corrugation in the mitre bends was optimized for low phase errors of the propagating modes, which is achieved by an increased corrugation depth and a corrugation direction, which is rotated by 45°. Furthermore, calculations show, that the wall fields are very high near the mitre bends, which explains the strong heating in this area.

| Angle | Par. pol. | Perp. pol |
|-------|-----------|-----------|
| $0^\circ$ | no arcs | 1.4 ms @ 500 kW |
| $2.5^\circ$ | no arcs | no arcs |
| $5^\circ$ | 1.4 ms @ 600 kW | 10 ms @ 500 kW |
| $7.5^\circ$ | no arcs | 4 ms @ 500 kW |
| $10^\circ$ | no arcs | 2 ms @ 500 kW |
| $12.5^\circ$ | 1.5 ms @ 450 kW | 1 ms @ 500 kW |

Table 2. Arcs observed in the waveguide with 2 mitre bends. The time values are the pulse durations, after which the arc occurred.

8. Consequences for the application on ITER at 170 GHz

In the following, some consequences as well as possible improvements for the application on ITER at 170 GHz are discussed. It is assumed, that the waveguide consists of pure copper and is operated at a surface temperature of 200°C. The waveguide cross-section is quadratic with $a = 44$ mm, the length is taken as $L = 4.33$ m. The power at the waveguide entrance is 2 MW.
8.1. Input beam and radiation patterns
For the mock-up tests a small ratio between input beam waist $w_0$ and waveguide width $a$ of $w_0/a = 0.28$ was chosen. This is not optimum with respect to beam divergence, however, it does strongly reduce the risk of arcing at the waveguide entrance and in the mitre bends. By careful optimization of the input beam with respect to width and amplitude profile, a relative reduction of the beam divergence can be obtained. Limits are imposed by truncation of the input beam at the window and waveguide entrance (reflections!) as well as at the waveguide exit.

8.2. Ohmic loss

![Figure 10. Expected overall ohmic loss and peak heat load of the waveguide wall in both polarisations for the ITER RS launcher at 2 MW input power](image)

Based on low power measurements with the Remote Steering waveguide [2] and with the 3-mirror resonator [10], a scaling of the losses to ITER conditions was performed. The frequency in the low-power measurements was 158 GHz, which was found to be ideally matched to the corrugation profile. In Fig. 10, the expected overall ohmic loss in both polarisations for the ITER RS launcher is calculated, where a conductivity of the aluminium alloy used for the mock-up waveguide of 26 MS/m, a conductivity of copper at 200°C of 34 MS/m, and a wavelength ratio of 1.08 (170/158) has been used. In the same graph, the peak power wall loading for the first reflection is plotted, where an input beam with $w_0 = 15$ mm as is foreseen at present was assumed.

At the maximum steering angle of $\phi = 12^\circ$, a total ohmic loss of 4% is expected in the worst case (parallel polarisation) with a maximum wall loading of 2.3 MW/m². Note, that the operation of the upper launcher will be with elliptical polarisation, i.e. a mixture of parallel and perpendicular polarisation.

8.3. Mitre bends

The use of mitre bends in the upper launcher of ITER is possible, but the design and location of the bends should further be optimized. The strong heating of the waveguide wall in the mitre bends can be handled, but should be avoided as far as possible. One means is the positioning of the bends at places where the field strength on the wall is low. A first analysis of the problem shows, that the loss of the bends can be reduced if mitre bends with higher deflection angles are used. This leads to less rotation of the polarization and thus to a lower diffraction loss. Moreover, the depth of the grooves in the mitre bends can be reduced and therefore, the ohmic loss is reduced as well. Additional investigations are needed to further optimize the mitre bends along these guidelines.

8.4. Arcing in the waveguide

The tests of the mock-up were performed under atmospheric conditions, using a waveguide with rectangular corrugation profile (originally not designed for high-power). As ITER will operate
the launcher under vacuum and will use a rounded corrugation profile, the arcing limits should be much higher. Therefore arcing problems for ITER conditions appear not be a major problem provided that collection of dust in the grooves of the waveguide is avoided.

9. Summary
High power tests of the remote steering launcher were performed at 140 GHz at the ECRH facility at IPP Greifswald. Although the waveguide was manufactured only for low power tests, high power tests could be successfully performed under atmospheric pressure for the straight setup. The far field patterns confirmed earlier low power measurements resulting in a usable steering range of $-12^\circ < \phi < 12^\circ$. The absorption coefficients for a single reflection calculated from the temperature increase of the waveguide wall agree well with the low power measurements. From the values for one reflection, an estimation of the overall ohmic losses was performed. The results confirm and supplement experiments at JAERI [14] performed on an evacuated waveguide at 170 GHz. No major obstacles were identified so far for the application on ITER, even at a 2 MW level.

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