CONSIGLIO NAZIONALE DELLE RICERCHE

Conceptual design of a quasi-optical transition from rectangular oversized waveguide to corrugated waveguide

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Introduction

At the current stage of design of the ICRH antenna for ITER by the CYCLE Consortium [1], a reflectometer is used for edge plasma density measurements [2]. The transmission line inside the Port Plug (PP) is WR28 rectangular waveguide, used for the 50-150GHz band.

Transition to a larger waveguide outside the PP is mandatory for the long transmission line to the instruments, because of losses. Corrugated circular waveguide, as used in JET [3], would be very convenient for the task.

This report provides a conceptual study for assessing the expected performance of a quasi-optical transition based on the same concept as JET's Quasi Optical Boxes (QOB) [4].

First-order calculations are made using the first Gaussian beam TEM_{00}, and Physical Optics simulations with GRASP™[5] are used to validate results and compute the coupling between the ports of the device.

This study is provided as a voluntary contribution outside the Third Party Agreement [6] between CEA and IFP for electromagnetic design of a reflectometer window.

Conceptual design

Assumptions

The frequency band is very close to the 60-160GHz of the QOB design, so it is assumed that the same corrugated waveguide is used. It is assumed that a pure HE_{11} exists in the corrugated waveguide, although simulations are made taking into account the variation in mode balance with frequency. Ohmic losses are neglected, being smaller than coupling and diffraction ones. Similarly, reflections at the waveguides are neglected.

General structure

The proposed design consists of a confocal telescope of suitable magnification, made with elliptical mirrors, coupling the field at the aperture of a suitable rectangular horn with that at the corrugated waveguide aperture.

The focal length of the mirrors is a free parameter, but placing them at the mid-band Rayleigh distance from the corrugated waveguide aperture is bound to minimize aberrations due to mis-match of the phase front at that frequency. A further degree of freedom is the angle of incidence of the beam on the mirrors, that can be reduced as much as practicable, in order to make the system closer to ideal.

The corrugated waveguide is assumed of 31.75 mm diameter, with *w=0.5mm, p=0.75mm, d=0.63mm*, where *w,p,d* are respectively the width, period and depth of the corrugation, as the one used at JET, even if the one with *d=0.8mm* has slightly better performance for the frequency band of this project [3].

A balanced HE_{11} of a corrugated waveguide is best coupled with the TEM_{00} mode with waist of $0.6435\ a$ at the aperture [7]. i.e. about *10.7mm* for the waveguide under consideration. The corresponding Rayleigh distance is

$$z_R = \frac{1}{2} k w_0^2$$

varying between 55mm at 50GHz and 164mm at 150GHz. At the midband frequency of 100GHz it is about 109mm. A focal length *f=110mm* appears adequate and reasonably compact. As a consequence of this choice, the frequency-dependent mid-waist is $w=2f/kw_0=20.5mm$ at 50GHz to *6.87mm* at 150GHz.

The best coupling between a Gaussian beam and a rectangular waveguide (see Appendix) is obtained for *w/a=0.352, w/b=0.505* where *a,b* are the broad and narrow sides of the waveguide. Choosing *a=29.0mm* and *b=20.2mm* one can obtain optimum coupling with the same beam radiated from the corrugated waveguide. Since this is a perfectly manageable size, one can choose unit magnification for the telescope and have a single type of mirror.
The width of the mirrors should be chosen on the ground of optimum truncation. As a guideline, if the phase curvature in the E-plane of the horn aperture is neglected (i.e. assuming the horn is actually a waveguide), the far field in this plane is that of a uniform aperture, with the first zero at $\theta = asin(\lambda/b)$. The elliptical mirror transverse size in this direction should approximately match this at miband. This ranges from 12deg at 150GHz to 38deg at 50GHz, being 18deg at midband (100GHz). At the distance of 110mm, the resulting mirror width is 71.5mm, approximately the same width as the QOB mirrors, with a beam truncation of *3.1w* at 100GHz.
The phasefront curvature at the aperture of a rectangular horn could be removed using a parabolic-horn antenna instead [8].
The equation of a parabola in polar coordinates (origin at horn apex) is

$$\rho = \frac{2f}{1 - \sin\varphi}$$

with $-\varphi_0 < \varphi < \varphi_0$ defining the horn.
Assuming a reasonable length for the horn (e.g. 150mm slant length), the boundary condition is that the lower edge of the parabola ($-\varphi_0 = \varphi$) is at 150mm, i.e.

$$\frac{150}{\cos\varphi_0} = \frac{2f}{1 + \sin\varphi_0}$$

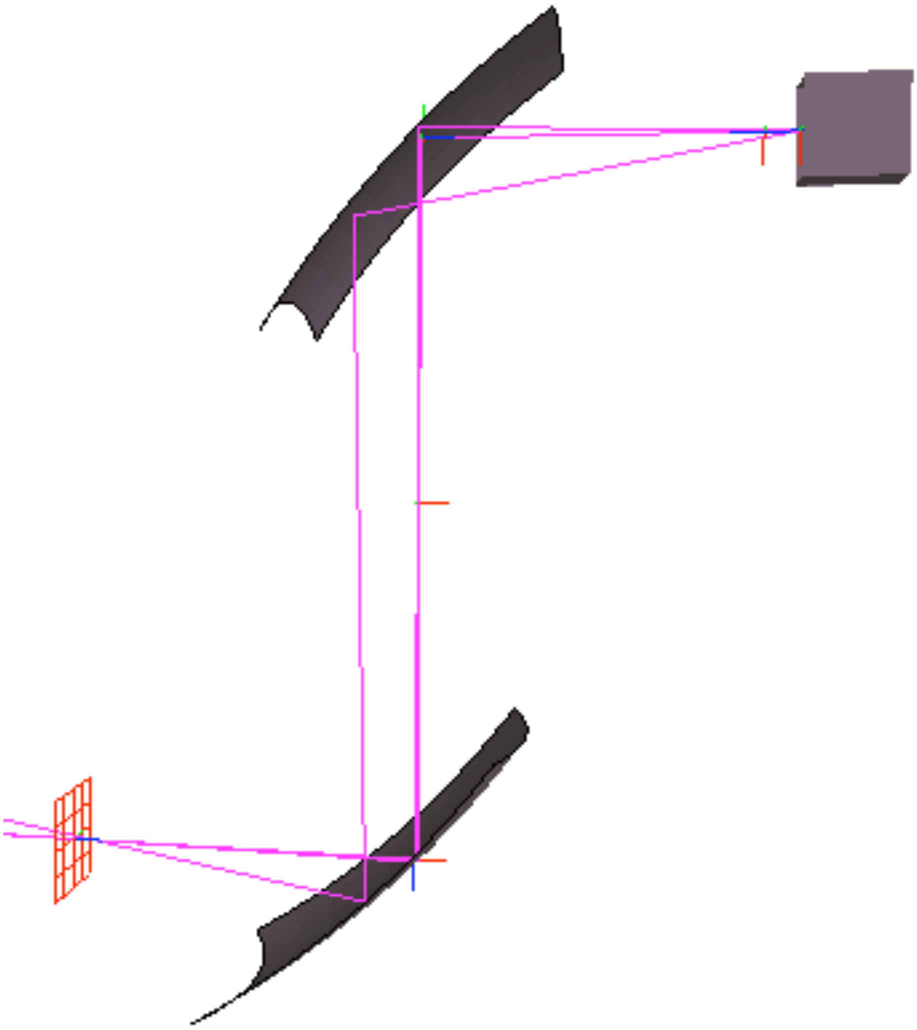
whereas the upper edge ($\varphi_0 = \varphi$) is at 150+29mm (for an aperture of 29mm), i.e.

$$\frac{150 + 29}{\cos\varphi_0} = \frac{2f}{1 - \sin\varphi_0}$$

As a result, one gets φ_0=5.057 degrees and *f=81.93mm*.
The resulting parabola is *extremely* close to a plane, so it is probably much simpler to have a longer horn, rather than manufacturing a complex piece with tight tolerances.

Simulations

The simulation was set up with GRASP, starting from the set used for the QOB, and using the same frequencies (60, 120, 160GHz) to begin with, in order to re-use the available HE_{11} field maps at the corrugated waveguide aperture. The beam incidence on the mirrors is at 45 deg, so that incident and reflected beams are perpendicular.
The rectangular horn was at first simulated with a waveguide of the same aperture (i.e. assuming a perfect correction of the phasefront curvature, either obtained with a parabolic horn antenna or with a very long rectangular horn).
A sketch of the geometry is shown in the figure below (taken from a GRASP screenshot).



Geometry of initial simulation. Top right the rectangular horn (simulated with a rectangular waveguide), reflection at two elliptical mirrors in confocal arrangement (center ray and one ray in either plane are shown) and the grid (bottom left) where the HE_{11} mode field is defined (computed externally).

The waveguide size was varied by 10% in either direction and in both dimensions, obtaining the following insertion losses at 60,120,160GHz:

	a=25	a=29	a=33
b=18		-.67,-.48,-.58dB	
b=20.19	-.70,-.47,-.49dB	-.64,-.40,-.40dB	-.69,-.52,-.53dB
b=21		-.67,-.39,-.39dB	

As expected, the design parameters are near optimum.
The position of the rectangular waveguide along its axis was varied too by +/-10mm:

z=-10	-.68,-.41,-.40dB
z=0	-.64,-.40,-.40dB
z=10	-.65,-.42,-.41dB

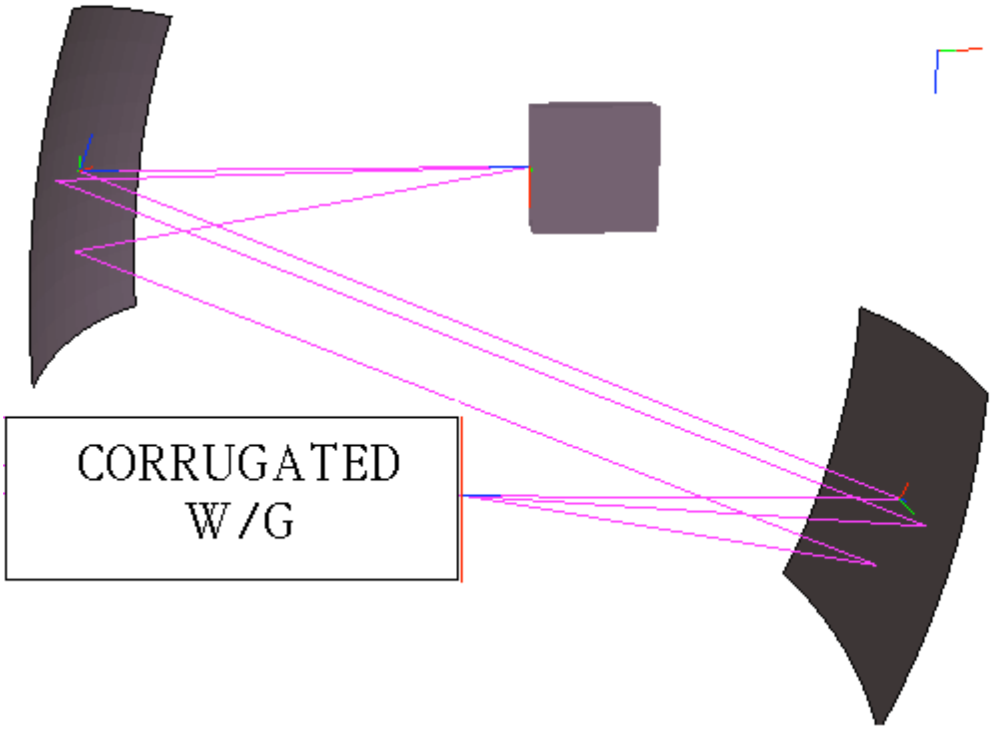
Again, as expected given the flatness of the phase front, the design positon is optimal.
The very same calculations were repeated using a rectangular horn of 150mm flare length, obtaining these results for the insertion loss as a function of aperture size

	a=25	a=29	a=33
b=18		-.80,-.88,-1.38dB	
b=20.19	-.82,-.84,-1.27dB	-.79,-.84,-1.34dB	-.87,-1.01,-1.55dB
b=21		-.83,-.86,-1.37dB	

and position along the axis

z=-10 (far)	-.91,-.88,-1.34dB
z=0	-.79,-.84,-1.34dB
z=10 (near)	-.71,-.84,-1.33dB

As expected, the optimum aperture size is close to the one chosen, whereas coupling improves if the horn is displaced towards the mirror, because the curved phasefront is better matched to the converging beam. The amount of the displacement along the horn axis is very small. More relevant results could be obtained moving the flared horn much nearer to the mirror, because the horn flare length of 150mm, which is not much larger than the beam curvature radius at the first mirror.
A more compact version of the taper could be obtained by reducing the angle of incidence (which has the added bonus of reducing aberrations and eventually allowing the use of cheaper spherical mirrors). The structure becomes more and more folded. Of course it could be folded further by the addition of flat mirrors, but this development should be dictated by mechanical constraints only.
The picture below shows a near-side-view of the folded arrangement.

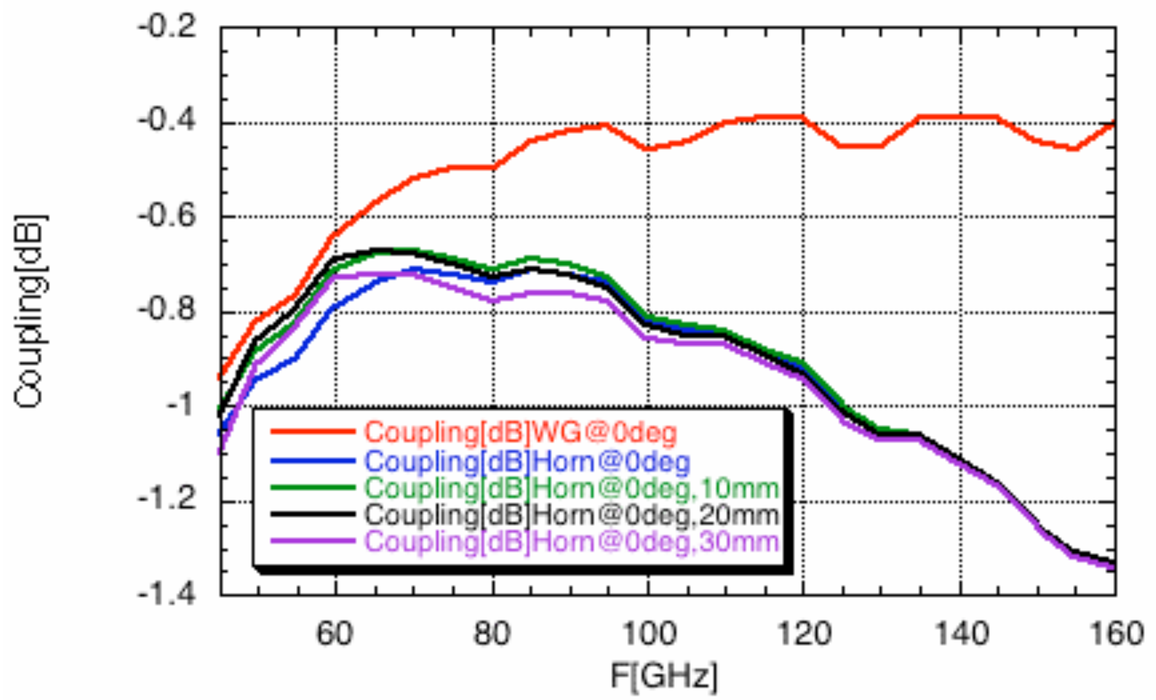


Geometry of a transition with lower angle of incidence. The horn (rectangular waveguide) is top right, and three rays are shown per beam, the central one and one for each polarization plane.

The table below shows the results for a waveguide of nominal size varying the reflection angle.

angle [29x20.19mm]	Coupling loss [dB]
22.5 deg	-.51,-.34,-.37dB
45 deg	-.53,-.35,-.37dB
90 deg	-.64,-.40,-.40dB

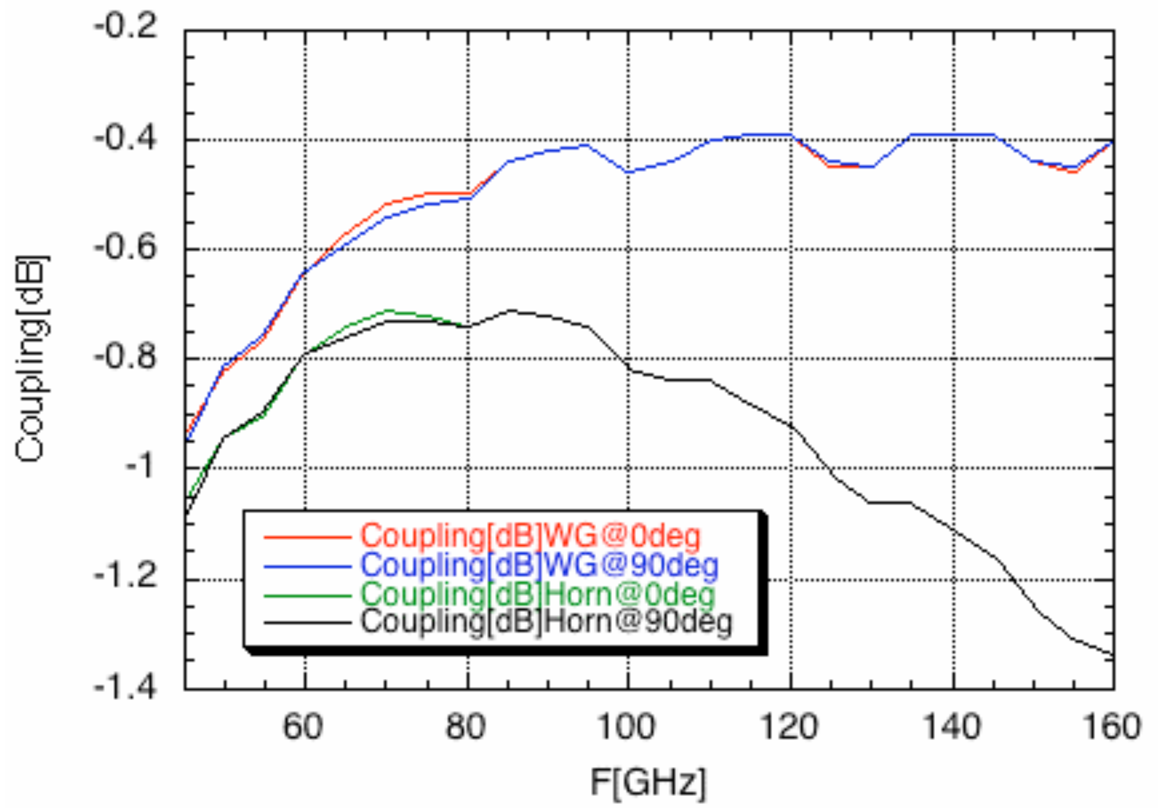
As expected, performance improves as the angle of incidence is reduced.
Of course the 22.5 deg is a rather extreme case (obstruction neglected) unless the structure is folded using flat mirrors.
Having confirmed that the performance is reasonably optimal at the chosen design configuration, one needs to assess the frequency variation in performance, in order to build a feeling on the relative importance of the variations found.
The HE_{11} was computed at the corrugated waveguide aperture between 45 and 160 GHz in steps of 5 GHz, and coupling was computed with GRASP as usual in the configuration at perpendicular reflection.
The result is shown in the figure below for the waveguide (infinitely long or perfect parabolic horn) with the red curve, and for a 150mm flare length horn at its nominal position and displaced by 10, 20, 30mm towards the mirror.



Coupling between HE_{11} in corrugated waveguide and TE_{10} in rectangular waveguide (red trace, top) or 150mm horn (blue curve, bottom). The horn was displaced by 10 (green curve), 20 (black), 30 mm (purple) towards the mirror, to match the phasefront curvature of teh Gaussian beam at least at one frequency. Best performance is for a displacement between 10 and 20mm.

The best result for the horn is obtained for a displacement of about 10mm towards the mirror (green curve). Longer horns or real parabolic horns are expected to give coupling losses between those of the waveguide and those of the 150mm horn. As horns get longer and longer, the region of optimum performance shuld move to higher and higher frequencies, and the shift required on the horn should get smaller, in accordance with the behaviour of the phasefront curvature radious in Gaussian beams.

The polarization sensitivity of the scheme was checked by computing the coupling loss for TE and TM polarizations (i.e. E or H field perpendicular to the plane of incidence). No significant difference was found, as shown in the picture below.
Therefore, provided one chooses the TM polarization and properly takes into account refraction on the beam axis, this configuration makes the transition an *excellent* place for a Brewster window.



Coupling between HE_{11} in corrugated waveguide and TE_{10} in rectangular waveguide (top curves) or 150mm horn(bottom ones) for the reference (TE) polarization and for a 90 degrees rotation into TM polarization. No significant difference is seen, as expected for the perpendicular reflection scheme.

Discussion

The present study shows that one could expect a coupling loss not worse than 1.2 dB over the full bandwidth, with a reasonably compact and easily manufacturable structure. Expected upper and lower boundaries have been set on performance, depending on horn optimization.
A Brewster window could be easily integrated in the component (provided that the angle of incidence is properly chosen for the material of interest, e.g. 62.9 degrees for quartz).
Further optimization could be done by taking into account mechanical and geometrical constraints, especially taking care of the position of input and output waveguides, that are rather diffucult to accommodate along the same line.

Appendix

Coupling between Gaussian beam and rectangular waveguide

The coupling coefficient is defined (in scalar approximation) *at the waist plane* as

$$C = \left| \int_A \psi_w(x,y) E_{a,b}(x,y)\, dxdy \right|^2$$

where

$$\psi_w(x,y) = \frac{2}{w} \exp\left(-\frac{x^2}{w^2} - \frac{y^2}{w^2} \right).$$

and

$$E_{a,b}(x,y) = \frac{1}{\sqrt{ab}} \cos\left(\frac{\pi x}{a} \right)$$

are the field functions of the TEM_{00} and TE_{10} modes.

Phase terms have been neglected since computation is performed at the waist, where the phase front is flat.

The result is

$$C = \left| \int_A \frac{2}{w} \exp\left(-\frac{x^2}{w^2} - \frac{y^2}{w^2} \right) \frac{1}{\sqrt{ab}} \cos\left(\frac{\pi x}{a} \right) dxdy \right|^2 =$$

$$= 32 \frac{a}{w} f\left(\frac{a}{w} \right) \frac{2w}{b} g\left(\frac{b}{2w} \right)$$

where

$$f\left(\frac{a}{w} \right) = \left| \int_0^{1/2} \exp\left(-\chi^2 \frac{a^2}{w^2} \right) \cos(\pi \chi)\, d\chi \right|^2$$

$$g\left(\frac{b}{2w} \right) = \left| \int_0^{b/2w} \exp\left(-\xi^2 \right) d\xi \right|^2$$

The maxima of

$$\frac{a}{w} f\left(\frac{a}{w} \right) \text{ and } \frac{g\left(\frac{b}{2w} \right)}{\frac{b}{2w}}$$

can be found at *a/w=2.84395*, i.e. *w/a=0.352* and *b/2w=0.989933,* i.e. *b/w=1.97988,* i.e. *w/b=0.505082*.

For optimum coupling with a gaussian beam, the w/g aspect ratio *b/a* must be *b/a=0.696171,* i.e. *a/b=1.43643*.

For a=29.00mm, b=20.19mm.

References

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