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THE HYPERGUIDE : A NEW CONCEPT OF LOWER HYBRID LAUNCHER

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ABSTRACT

The hyperguide is a new design concept which overcomes some of the technical problems associated with slow wave launching structures used for lower hybrid current drive and based on the conventional multijunction. Its simplicity makes it relevant to a reactor environment. Numerical simulations indicate that high power transfer efficiency is achievable.

INTRODUCTION

Slow waves in the lower hybrid range of frequency are now a well established method of current drive and profile control in tokamaks (1). The current drive efficiency is the highest so far up to 0.4 $10^{20}m^{-2}$ A/W and recent works (2) show that it can still be improved by synergistic effects when combined with ICRF heating and by increasing the wave frequency, particularly on high density plasmas. Plasma currents of up to 2 MA have been driven by Lower Hybrid waves both in JT-60 and in JET. Subject to finding a solution to the technical problems, it is potentially a relevant current drive method for a future thermonuclear reactor.

The major drawback of a Lower Hybrid Current Drive plant is the complexity of the wave launching structure. The only antenna concept available at present consists of a phased array of waveguides. The waveguides have to be as narrow as possible in order to achieve an N// index in the range of 1.5 to 2, which corresponds to the best current drive efficiency. Narrow spectra are also required to achieve high efficiency, and in order to create such a spectrum, a large number of waveguides in the toroidal direction are required. Fulfilling those requirements within the power density limits attainable in vacuum implies that the antenna mouth must consist of a very large number of waveguides. For instance, the JET launcher consists of 384 waveguides disposed in a 12 x 32 matrix (3).

Since the spectral quality of the launched wave depends on the precise phasing between adjacent waveguides, the design of the structures dividing the power from the generator into these waveguides is one of the main problems in a launcher design. As long as the number of waveguides is modest, an external waveguide splitter dividing the power outside the tokamak vacuum, and allowing the relative phasing to be changed by means of mechanical phase shifters is acceptable. But as soon as the number of waveguides increases, this solution becomes impractical, as it would require a large number of RF vacuum windows for the waveguides to penetrate into the vacuum vessel. Lower Hybrid launchers used on Tore Supra and JET (256 and 384 waveguides respectively) were therefore designed using the "multijunction" concept.

The multijunction is a device that divides the incoming standard waveguide from the generator into 8 narrow waveguides by means of one H and 6 E plane junctions under vacuum (see figure 1). The phase relation between adjacent waveguides is given by phase shifters embedded in the multijunction. The multijunctions are stacked and their faces welded together creating the waveguide array required to launch the slow wave. In JET, this arrangement allowed to feed a 128 prototype waveguide array with 8 klystrons requiring only 16 vacuum windows. The final system now being installed on JET will allow 24 klystrons to feed a total of 384 waveguides through 48 windows (figure 2).

The drawbacks of this type of antenna are many: it is obviously a complicated arrangement, difficult to manufacture, assemble and install and heavy to support. Since the multijunctions are all stacked together, vacuum pumping of the inside of the waveguides is very poor, resulting in gas accumulation which reduces the power handling capabilities of the antenna either through arcing or by creation of absorbent plasmas, particularly where the power goes through the electron cyclotron resonance layer.

As the front face of the antenna is also the front piece of the multijunction, this arrangement is probably not realistic in a reactor, where the need will arise of replacing the mouth of the antenna as it is slowly eroded by the plasma. A reactor design will also require a launcher with lower RF losses and simple cooling arrangements for quasi-steady state operation. It is also very doubtful that this concept can be used for large systems at frequencies of around 6 GHz and above, since the manufacturing tolerances and the dimensions of the waveguide components become unmanageable.

For these reasons, research has started to develop a concept that would be free from those objections.

THE HYPERGUIDE

The proposal is to build a launcher based on a transfer cavity. On the generator side the cavity is closed by an emitting surface consisting of an arrangement of waveguides feeding the cavity. On the plasma side, the cavity is terminated by a structure coupling the electromagnetic wave induced in the cavity to a slow wave inside the plasma. The design of the system can therefore by divided in three elements: The emitting surface (emitter), the cavity and the coupling structure (receiver).

The hyperguide proposal is based on a general idea: to find a transfer cavity and an emitter such as to transfer the power from the fundamental mode of propagation of the incoming waveguides (TE_{01}) to a privileged mode propagating in the cavity. The selected mode must also couple in the plasma side of the cavity to a structure (or "receiver") able to launch a slow wave into the plasma. This approach differs from a quasi optical approach in the fact that it assumes a low Q cavity strongly coupled both at the generator and the plasma end.

The proposed choice for the cavity is an overmoded waveguide. Its transverse dimensions have to be chosen to accommodate the emitter, which consists in a simple array of standard waveguides (figure 3). Our choice of a mode for the hyperguide is the TE_{0N}, where N depends on the number of rows of waveguides in the emitter, and is independent of the number of columns. This choice is prompted by the fact that the mode electric field at the interface with the emitter is given by the expression:

$$E = A \sin\left(N \frac{x}{a}\right)$$

where a indicates the height of the hyperguide. If we consider the wall thickness to be zero, we can write:

$$a = N a'$$

a' being the height of each individual waveguide in the emitter. Therefore

$$E = A \sin\left(\frac{2}{a'}\right)$$

corresponds to the electric field of a TE_{01} mode with zero phase in the even numbered emitter waveguides and with 180° phase in the odd ones, as can be seen in figure 3a. The extension of this principle to the full system can be seen in figure 3b. The electric field shape of the TE_{0N} mode matches almost perfectly the fields corresponding to TE_{01} modes in the incoming waveguides provided that:

i) adjacent rows are fed at the same power.

ii) adjacent rows are phased with a 180° phase difference between rows.

iii) adjacent waveguides in a row are fed in phase.

To take into consideration the finite width of the walls and the possible effects of irregularities in the symmetry of the system, a numerical code based on mode matching at the emitter-hyperguide and hyperguide-receiver interfaces has been developed. It considers a receiving structure constituted by reduced waveguides. The code takes into account up to 6 modes in each of the smaller waveguides and up to 200 in the hyperguide cavity (5). Computations were carried out considering an emitter configuration consisting of a 12 rows and 4 columns standard waveguide (34 x 72 mm) matrix, and a receiving surface consisting of a 12 x 16 matrix of reduced waveguides (7.7 x 72 mm). The waveguide wall thickness was set to 1 mm. The behaviour of the system can be characterised by a transmission quality factor Q_T, a mode quality factor Q_M and a distribution quality factor Q_D. Q_T is defined as the ratio between the total power leaving the hyperguide through the receiving surface and the total power entering the cavity through receiver and emitter waveguides. Q_M is defined as the ratio between the power transported by the TE_{012} mode and the total power entering the hyperguide cavity. Q_D is the maximum relative deviation of the power in the individual receiver waveguides with respect to the average value.

Three cases have been simulated with this code:

1. Ideal case: The input waveguides are fed with 1 W each (with constant phase in each row and 180° phase difference between rows) and no reflected power is coming back from the reduced waveguides into the cavity (figure 4).

2. Normal reflection case: The input waveguides are fed as in the first case, but a reflection of 10% at the grill mouth is simulated by injecting back some power through the receiver waveguides.

3. Trip case: A trip of the generator is simulated by setting to zero the power fed to two rows of the emitter (in our case, rows 5 and 6) (figure 5).

The results for these cases are summarised in the following table:

Case	Q_T	Q_M	Q_D
1	0.998	0.997	0.0
2	0.95	0.91	0.0
3	0.91	0.75	1.24

As expected, the ideal case gives results which are very close to the predictions of the simple calculations assuming zero thickness for the waveguide walls. A reflection of 10% does not perturbate the power distribution between the different output waveguides, and the system attenuates the power coming back to the generator from 10% to less than 5%. The third case shows that the tripping of two rows strongly perturbs the system. In fact this is not as serious as it seems. Although large differences appear in the power distribution between the different receiver rows, the power remains constant inside a given row. Each row will still be radiating a slow wave into the plasma. The tripping of one row does not induce a large reflection towards the generator, since 91% of the power is still transmitted.

The losses of a waveguide propagating a TE_{0N} mode are given by the expression (7):

$$p = K\frac{b}{a}\left(1 - \frac{\lambda n}{2a}\right)$$

where K is a constant depending on the wall material, b and a are the width and height of the waveguide respectively and λ is the vacuum wavelength. As the ratio b/a of the hyperguide is similar to the one of standard waveguides, the increase of the dimensions with respect to a single moded TE_{01} waveguide is compensated by the higher losses of a high order mode, and for a JET case (emitter composed by a 8 x 12 matrix, mode TE_{012}) the losses are about 5%, of the same order as for a standard waveguide transmission system.

The receiving structure design is much more delicate, as it constitutes the interface with the plasma and will be submitted to its eroding action. A set of solutions are envisaged, ranging from the classical waveguide structure to the more advanced diffraction based proposals (4).

The classic solution consists in terminating the hyperguide with a stack of reduced waveguides (figure 6) containing as many waveguide rows as there are in the emitter. Each reduced waveguide contains a phase shifter embedded in its walls. The TE_{0N} mode is then converted again in a TE_{01} dominant mode in each of the reduced waveguides (figure 3), and the phase shifters create the phase difference between adjacent columns required to launch the slow wave. The length of the reduced waveguide portion is then determined by the space needed to accommodate the phase shifters required to produce the appropriate slow wave spectrum.

Alternative proposals are in the preliminary stages of conception. They rely in the use of rods to diffract the incoming wave in order to operate a mode conversion between the incoming guided mode propagating in vacuum and the desired slow wave mode propagating into the plasma (4).

ADVANTAGES OF THE HYPERGUIDE APPROACH

The hyperguide approach has many advantages over the present Lower Hybrid antenna systems which could make it relevant for a fusion reactor design:

- The mouthpiece is decoupled from the rest of the cavity, and can therefore be modified or replaced without requiring the rest of the system to be dismantled. In particular, a reduced waveguide mouthpiece could be replaced remotely inside the machine by a more advanced one (like a diffraction rod type) as soon as it becomes available.

- The structures required in a hyperguide launcher are much lighter, simpler and cheaper to manufacture than in the conventional approaches.

- The hyperguide surface exposed to the microwave power is smaller than in the other types of antennas, and the cavity is much easier to pump. A hyperguide cavity replacing the present multijunction system installed at JET (figure 7) would have an exposed surface area of about 7.5 m^2 to be compared with 25 m^2 at present (both figures do not include the mouthpiece). As the power goes through the electron cyclotron resonance within the hyperguide, this could solve the power handling problems linked to the accumulation of gas, allowing the system to operate in CW conditions.

- Finally, as the hyperguide is not a resonant cavity, there is no inconvenience in extending its length. It is conceivable therefore to place the emitter surface outside the main shielding of the machine, allowing the vacuum windows and the associated electronics to be outside the high radiation area. Such an arrangement can be seen in figure 8. In the same way, the possibility of replacing the numerous individual windows by a single one installed inside the hyperguide would still simplify the system and improve its reliability.

CONCLUSION

The integration of an LHCD system on any fusion reactor design was up to now hampered by two fundamental problems: The complexity of the structures required to launch the slow wave, and the difficulty of protecting the vacuum windows and replacing them in the event of failure. The hyperguide concept answers these questions by means of a simple structure, flexible enough to accommodate new developments (particularly on the mouth structure arrangement), with the added possibility of removing the windows from the immediate vicinity of the machine. Numerical simulation indicates that this concept is feasible, and experimental testing should be done in order to confirm these results. We trust that this proposal will contribute to make the Lower Hybrid Current Drive advantages available to the ITER experiment.

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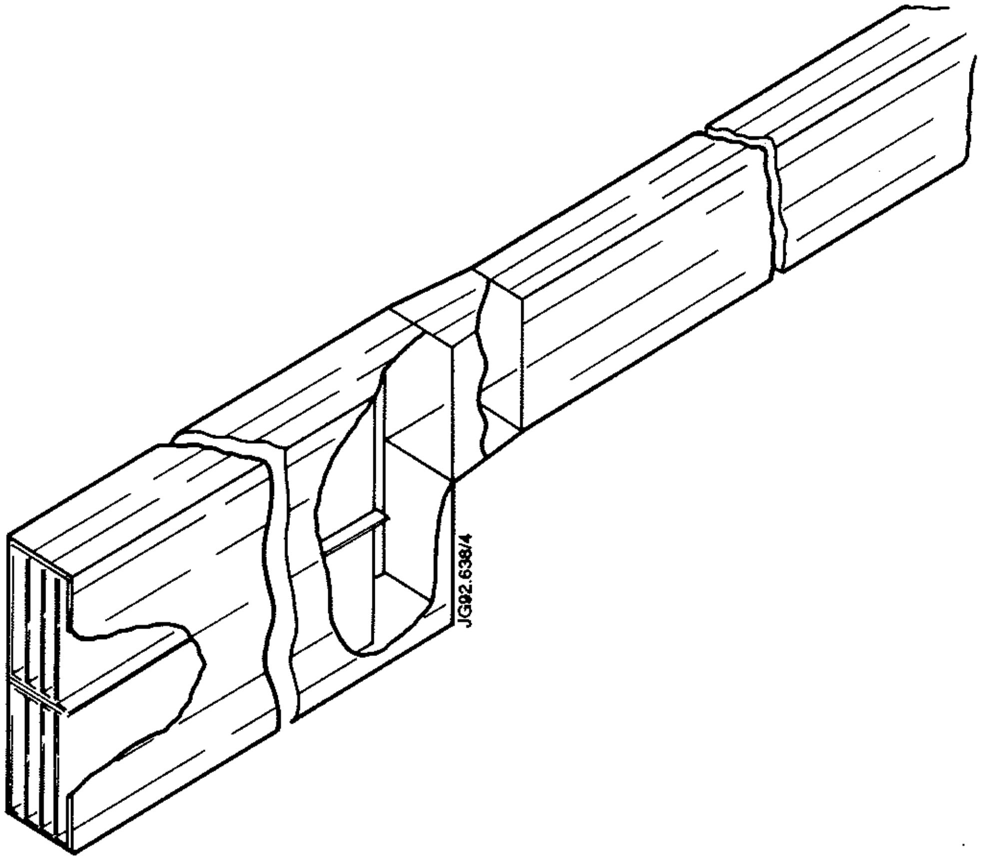

Figure 1: Overview of a multijunction.

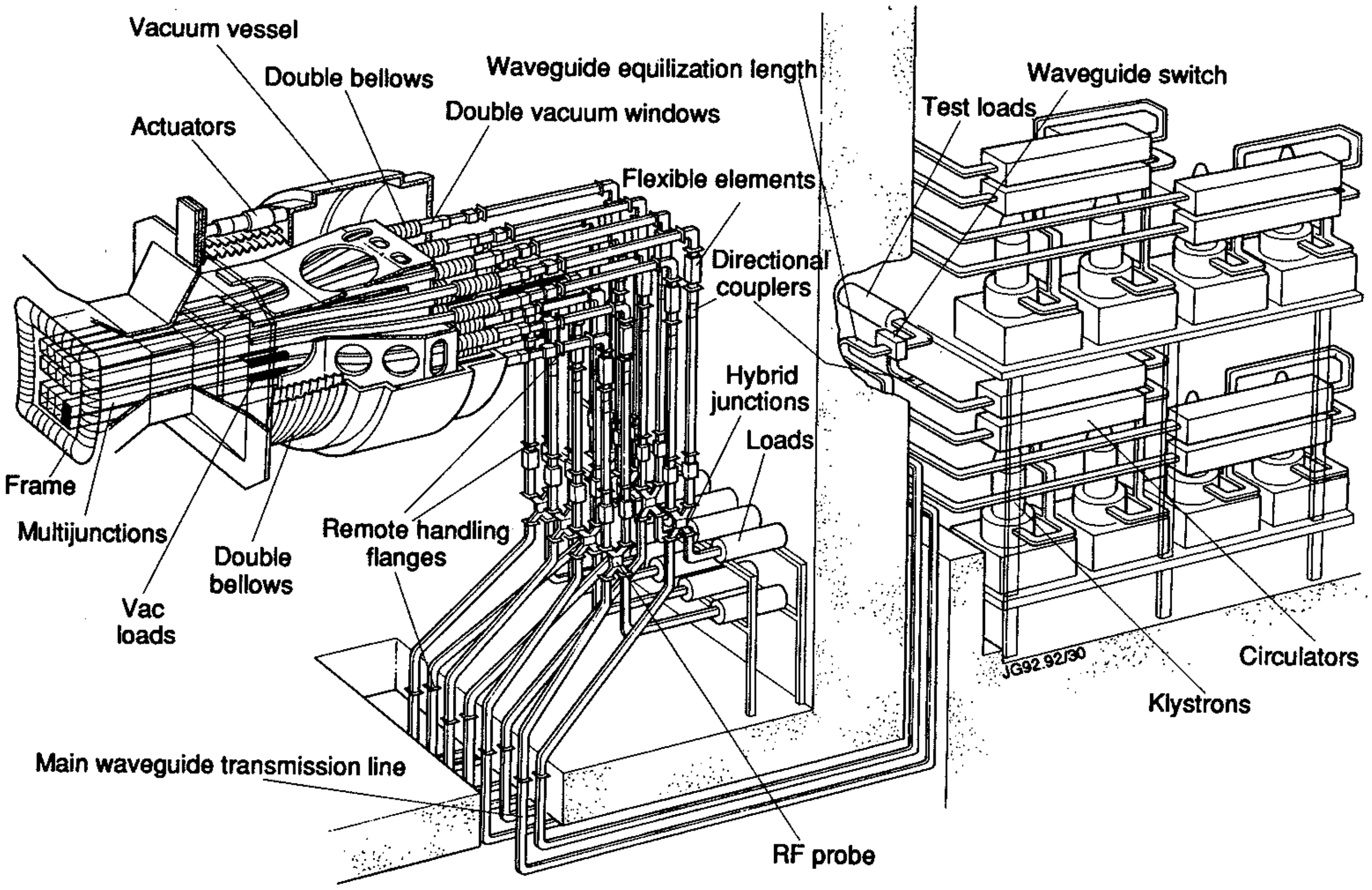

Figure 2: The LHCD system on JET
The complexity of the multijunction arrangement and the large number of windows present in the vicinity of the machine is apparent.

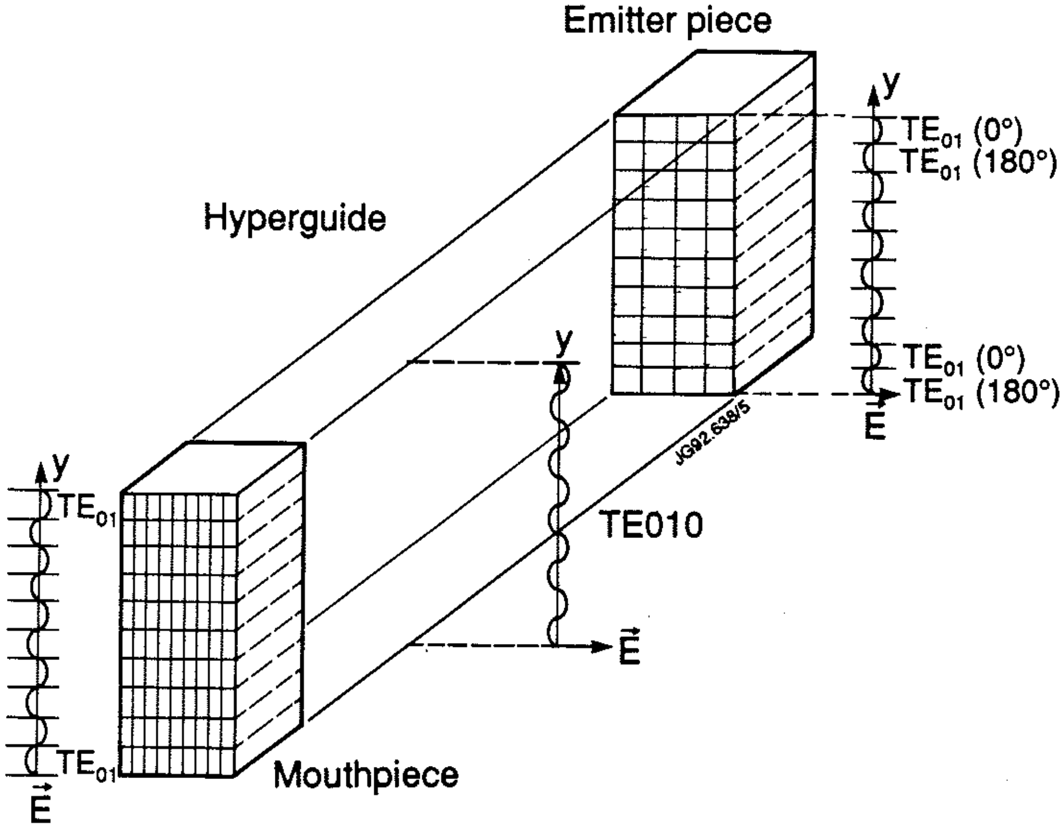

Figure 3a: Principle of the hyperguide cavity.
The input matrix is composed of 10 rows of waveguides fed in the TE_{01} mode, with the 180° phasing between rows. The electric fields couple almost perfectly to the TE_{010} mode in the cavity. The same principle applies to the mouthpiece waveguides.

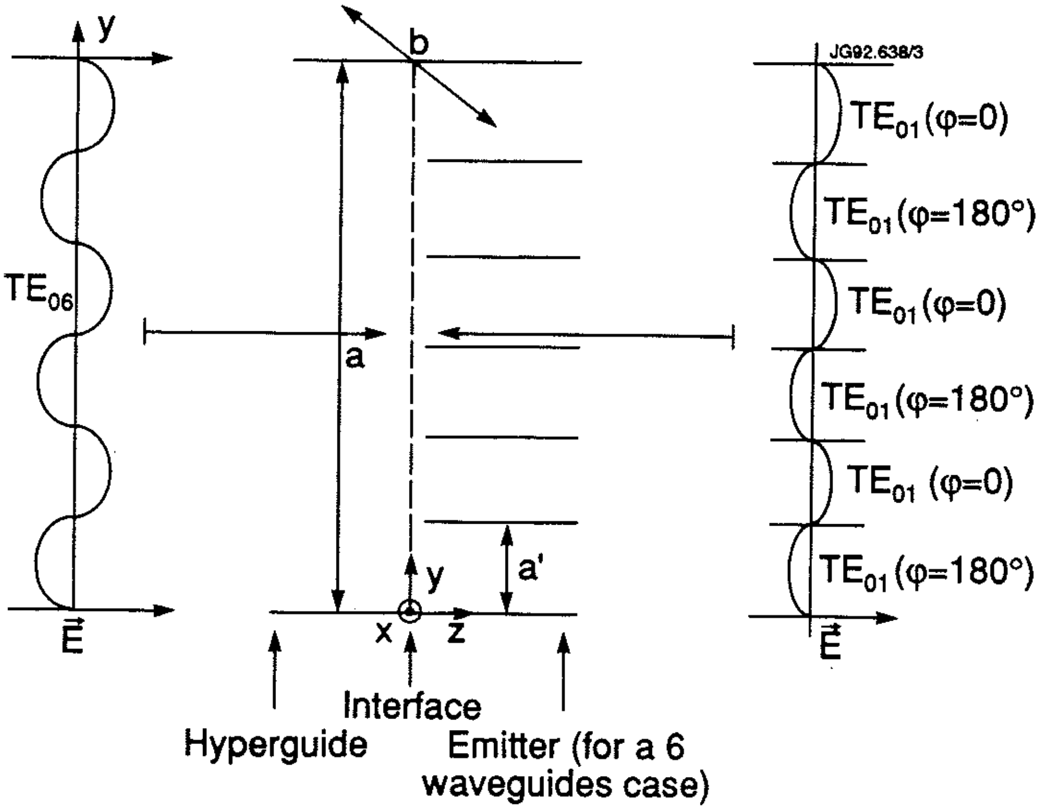

Figure 3b: Field matching at the emitter surface.
This vertical section of the hyperguide shows the matching between electric field in the incoming waveguides (fed in the TE_{01} mode with equal amplitudes and 180° phasing between rows) with the field of the TE_{0N} mode in the hyperguide.

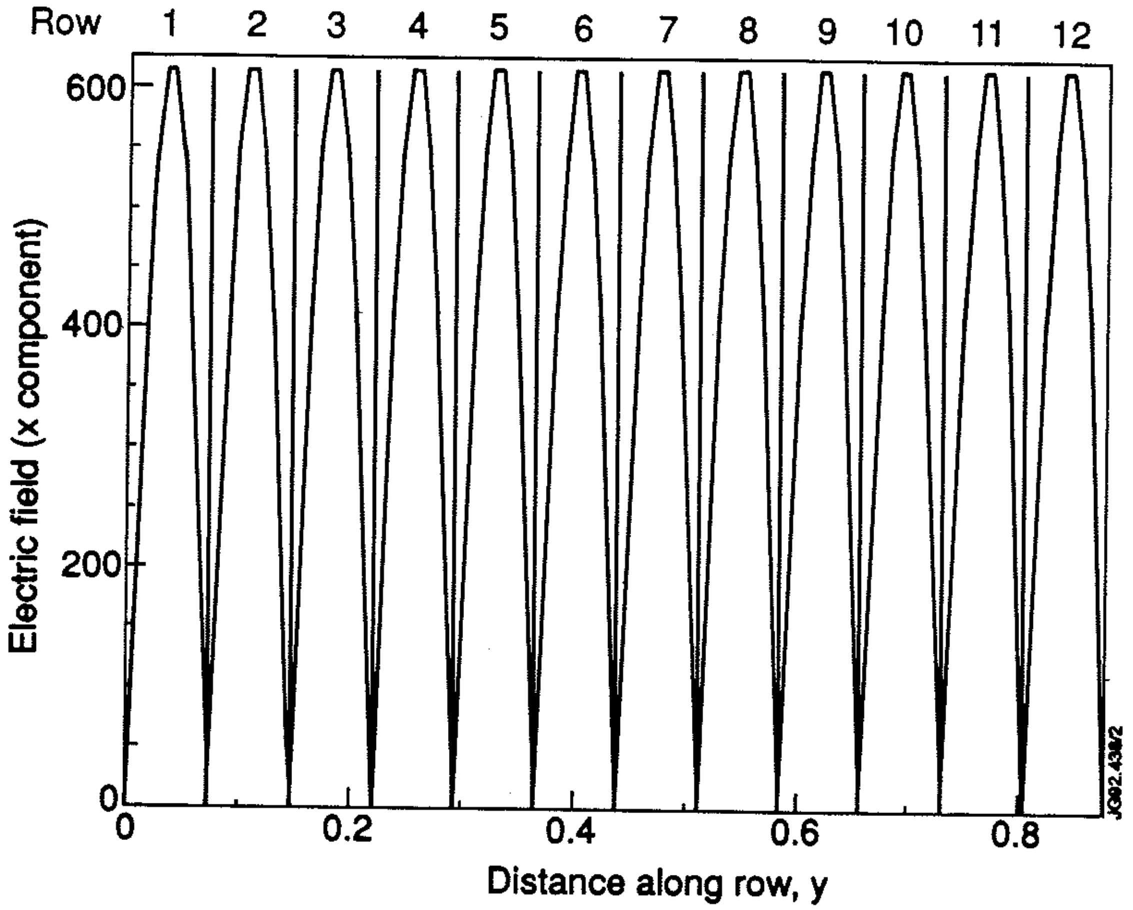

Figure 4: Electric field amplitude distribution along a column of the emitter surface (unperturbed case).

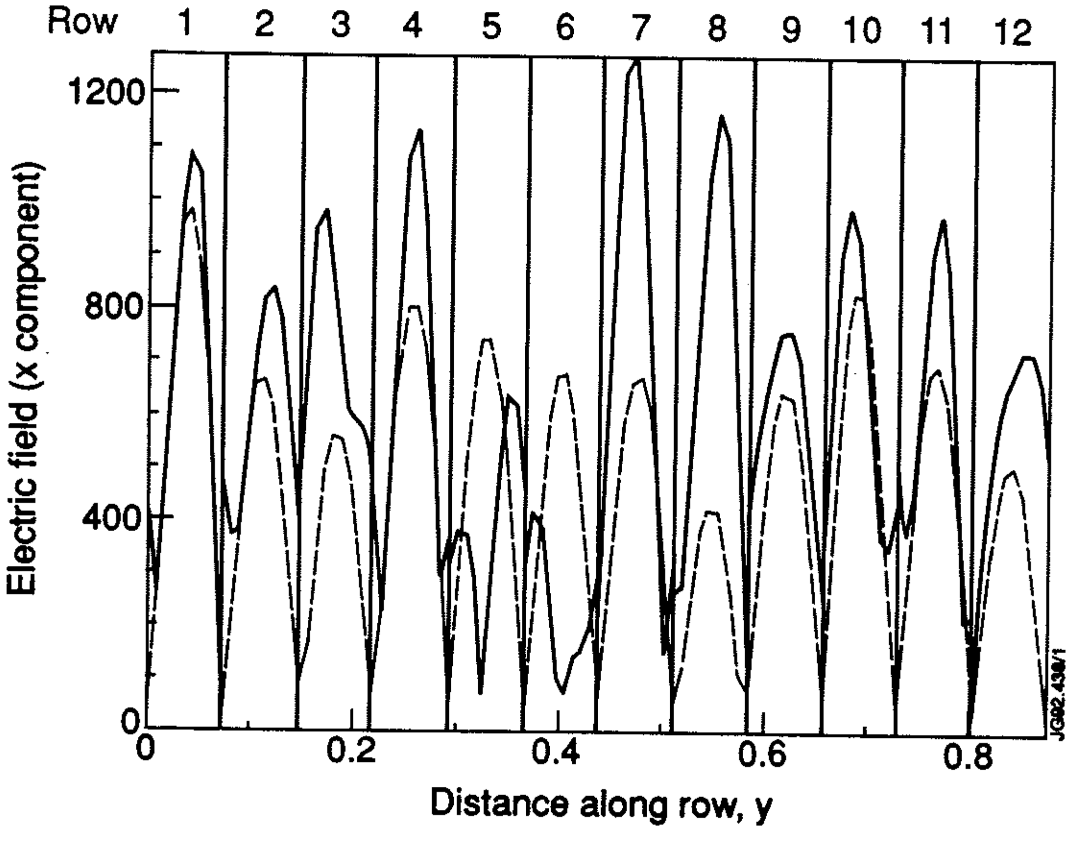

Figure 5: Electric field amplitude distribution along a column of the emitter surface (after a partial generator trip).

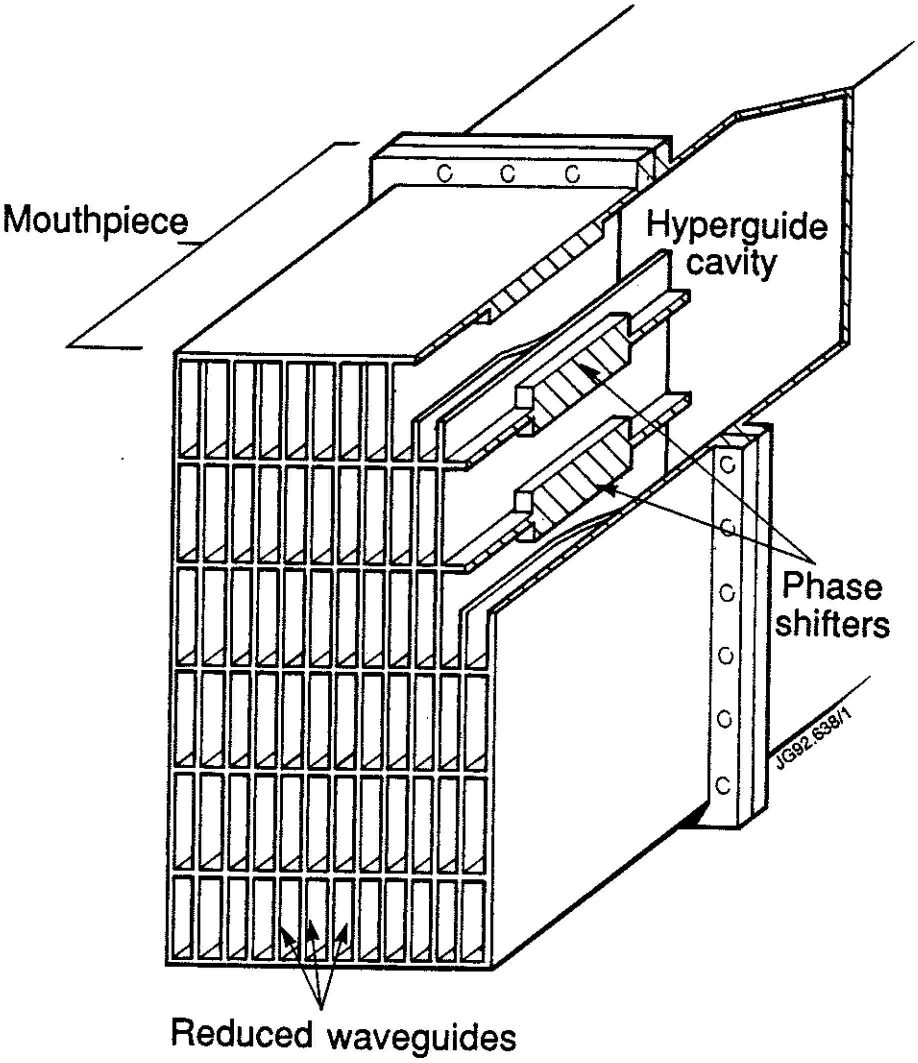

Figure 6: A possible mouthpiece design for an hyperguide launcher.

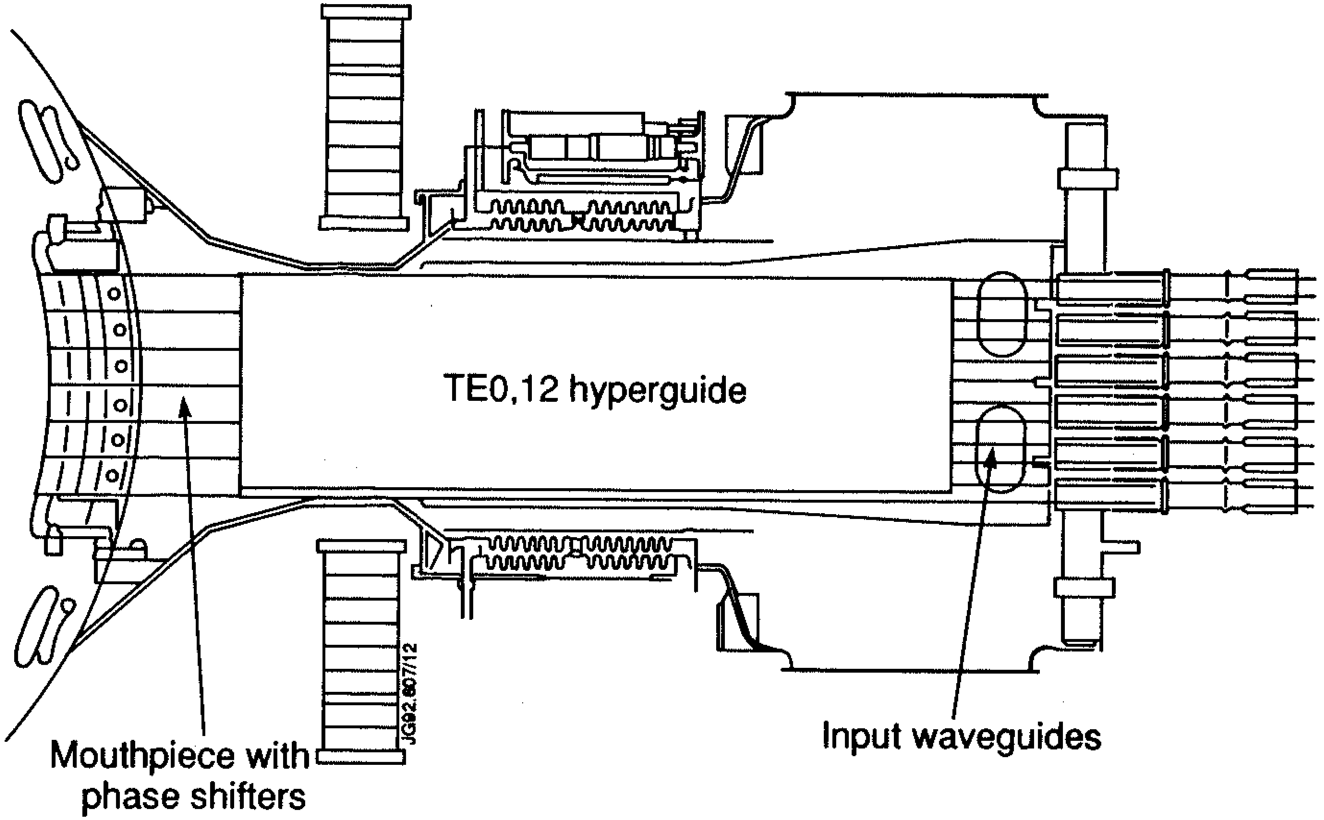

Figure 7: The hyperguide as it could be built into the JET device.

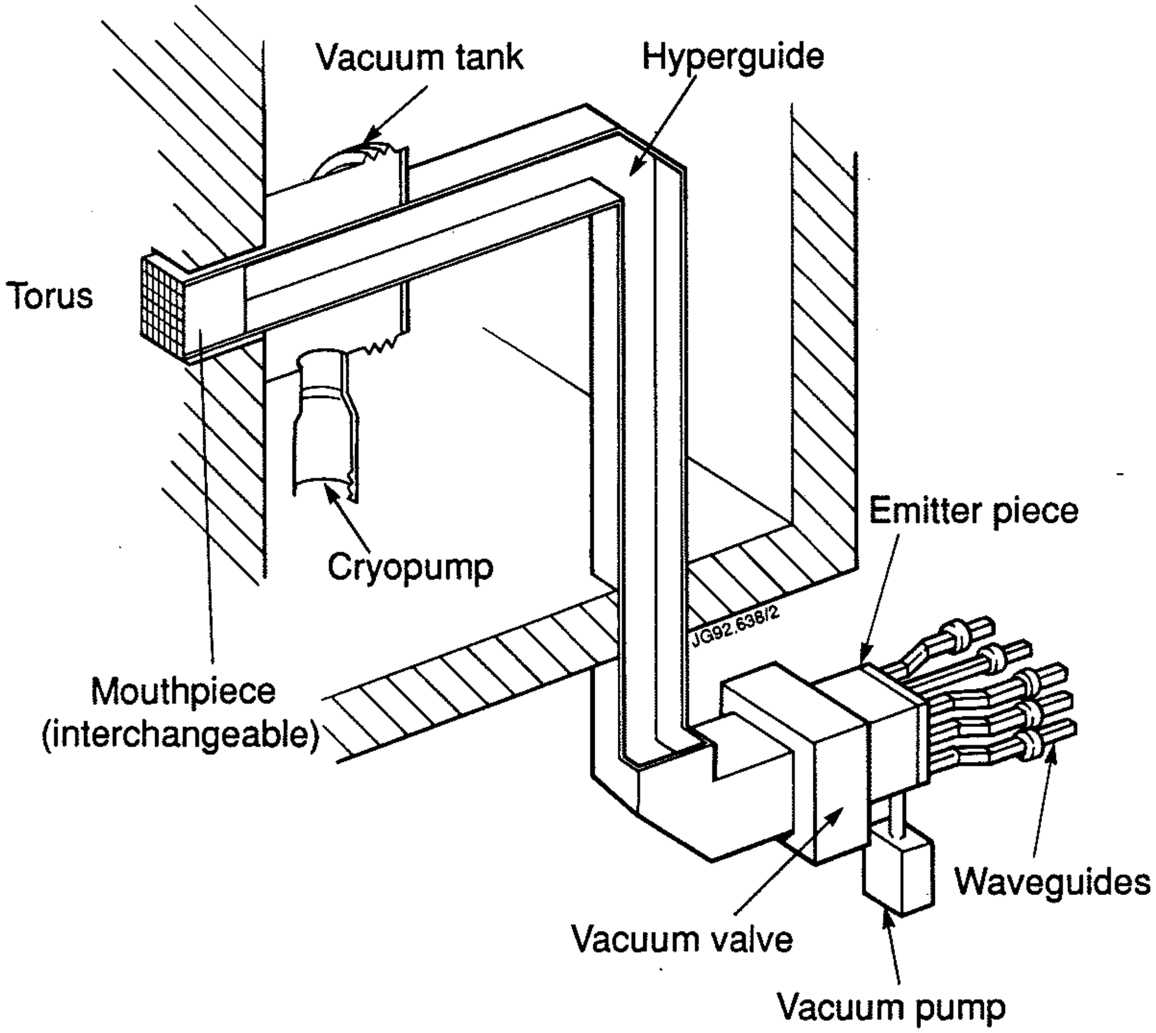

Figure 8: A conceptual view of a hyperguide based LHCD system in a future thermonuclear reactor. In this proposal the hyperguide cavity is used as an overmoded waveguide to transport the power, thus placing the windows far from the device itself.

Appendix I

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