

LRP 719/02

January 2002

**CRPP's Evacuated Waveguide Proposal
for JET-EP ECRH Transmission Line**

M.A. Henderson, S. Alberti, T.P. Goodman,
J.-P. Hogge, L. Porte & M.Q. Tran

CRPP's Evacuated Waveguide Proposal for JET-EP ECRH Transmission Line

M.A. Henderson, S. Alberti, T.P. Goodman, J.P. Hogge, L. Porte, M.Q. Tran.

Association EURATOM-Confédération Suisse
PPB – 222, CH 1015 Lausanne, Switzerland

Proposal for the installation of 8 lines of 45mm evacuated waveguides
for the JET-EP ECRH system. A comparison of this proposal
with the hybrid 87mm waveguide / quasi-optical system is included.

9 October, 2001

1	Abstract	3
2	Introduction	3
2.1	Potential breakdown on miter bends	4
2.2	Non-negligible microwave radiation in J1T	4
2.3	Significant volume occupied in J1T.....	4
2.4	Cost of the CVD windows and impact on the launcher	5
3	General overview	6
3.1	Description of the line	6
3.2	Accessibility to J1T and J1D	8
3.2.1	J1D Zone.....	8
3.2.2	J1T Zone	9
3.3	Tritium barriers	10
3.3.1	Torus barrier.....	10
3.3.2	J1D barrier	10
4	Waveguide elements	11
4.1	Matching Optics Unit.....	11
4.1.1	Universal Polarizer	11
4.1.2	Waveguide Coupling	11
4.2	HE ₁₁ Waveguide.....	13
4.2.1	Theoretical power handling	13
4.2.2	Present experience	13
4.2.3	Waveguide losses	13
4.2.4	Total HE ₁₁ associated losses	15
4.3	Miter Bends	15
4.4	Quasi-Optical Propagation	16
4.5	Total Transmission Losses	16
4.6	Temperature rise in Waveguide.....	18
5	Additional Waveguide elements.....	19
5.1	CVD diamond window.....	19
5.1.1	Resonant cavity between windows.....	19
5.1.2	Present experience	20
5.2	Load/Switch	20
5.3	DC Break	22
5.4	Pump out T	22
5.5	Support structure	22
6	Costs.....	22
7	Launcher.....	23
7.1	Description.....	23
8	Misc.....	25
8.1	Torus displacements.....	25
8.2	Power Calibration	25
8.3	Polarization Calibration.....	26

9	Schedule	26
10	Conclusion.....	27
11	Summary	30
12	Acknowledgements.....	31

1 Abstract

The goal of this document is to provide a detailed description of the preliminary design and technical information of a proposed evacuated transmission lines for JET-EP ECRH system. Three waveguide diameters (31.75mm, 45mm and 63.5mm) were studied and compared to the base design of the 87mm waveguide/quasi-optical proposal (WG87-QO). This report concentrates on only the 45mm waveguide diameter (WG45). This size represents an optimization between the flexibility of the smaller diameter and the low loss of the larger. For simplicity only the WG45 will be compared with the WG87-QO, but the other diameters (31.75 and 63.5 mm) should be kept under consideration for a final evacuated waveguide line. The characteristics of the 63.5 mm waveguide system can be found in the report which was distributed in September.

After an introduction of the history and motivation for this study a general overview of the proposal is presented. Sections 4 and 5 describe the elements to be used in the proposed line including the overall transmission losses for the line. Section 6 offers a cost comparison of the two proposals. The 7th section is a brief description of an alternative launcher design using the waveguide inserted into the launcher port. The 8th section describes the calibration and conditioning process to be performed after the line is installed and how the torus displacements will be handled. The 9th section describes the proposed schedule for purchasing and installation of the waveguide lines. Sections 11 and 12 include a conclusion and summary of the proposal.

2 Introduction

The original transmission system proposed for the JET-EP ECRH project involved an evacuated 63.5mm waveguide system (referred to as WG63). During the past year there has been a concentrated effort centered on investigating the possible use of a quasi-optical system. In March, 2001 a conceptual design of such a system was presented. With this system a ~30% reduction in the cost compared to the WG63 proposal was estimated¹. However, the JET Operator was concerned about the microwave leakage in the J1D building. This led to the currently proposed hybrid system of a combination of atmospheric 87mm waveguide in the J1D building and a quasi-optical system in J1T (this option is referred to as WG87-QO where WG87 refers to the 87mm waveguide section and QO refers to the Quasi-Optical section). The WG87 section of the line prevents radiation leakage within the J1D zone, while the quasi-optical section in J1T offers an economic means of transmitting the microwave power within the J1T zone. The overall design further decreased the costs of the transmission line to ~250k\$ per line (as of Oct. 2001, not including the CVD windows which were estimated to cost 245k\$). The WG87-QO is theoretically considered as an optimum delivery system in regards of the cost in delivering the microwave power from the gyrotron up to the first CVD window at the torus. But the optimization process does not include the CVD windows nor the launcher in its consideration

Despite the economic advantage of the WG87-QO proposal there are some drawbacks which should be considered:

- Potential for breakdown on miter bends
- Non-negligible microwave radiation in J1T
- Significant volume occupied in J1T

¹ Angela Curto, March 2001 design review meeting at JET

- Cost of the CVD windows and impact on the launcher

2.1 Potential breakdown on miter bends

The power density on the miter bend mirrors in WG87 is equivalent to 0.5MW in WG63. The WG63 system at CRPP is operated frequently with short pulse duration ($\leq 80\text{ms}$) under atmospheric conditions. This system is normally operated under high vacuum conditions ($\sim 10^{-8}\text{mbar}$) and is kept 'clean'. Despite the care taken, dust particles often enter the system and settle on the miter bend surfaces during brief openings even while continually flushing with dry N_2 . Breakdown occurs when the dust settles near the center of the mirror and results in pitting of the mirror surface. Every successive pulse results in breakdown at the pitted surface until the mirror is removed, polished and reassembled. Note, this implies fast easy access to upward facing mirrors and extra interlocks on the miter bend mirror will be needed. It is feasible to propagate the power densities required in WG87 in an atmospheric waveguide, but the risk of reduced reliability due to arcing is great.

Similar arcing problems on the miter bends in the atmospheric 89mm waveguide occurred at NIFS. The large waveguide diameter is fairly insensitive to the displacements of the beam at the input of the waveguide, but is very sensitive to tilts of the input beam. With only 0.5MW injected into the WG89 arcing occurred on the first miter bend due to such misalignments of the input beam.

CRPP expresses concern for the choice of using the WG87 under atmospheric conditions in light of the above two examples. Although the arcing problem can be overcome, the reliability of the system will be less than that offered from an evacuated waveguide line.

2.2 Non-negligible microwave radiation in J1T

In the WG87-QO there will be 0.03% scattered radiation from each of the 8 mirrors of the quasi-optical lines in J1T. Plus there will be additional scattered power coming from the non- HE_{11} modes radiated from the output of the waveguide and reflections from the CVD window. The non- HE_{11} modes come from the impurity of the gyrotron's output beam, mode conversion at each miter bend and mode conversion due to misalignment and bending in the waveguide. It is estimated that about 4.1% of the power in the waveguide will be non- HE_{11} modes for the WG87. An estimated 40 to 100% of that power will be transmitted through the waveguide and into the QO section (see Sec. III E.). The total scattered power per line would then be between 16 kW and 41kW depending upon how much of the non- HE_{11} modes are scattered in the QO section and assuming no power conversion due to misalignments and bending. There is a risk that the majority of this power will be radiated into the J1T zone. This level of stray radiation forces the use of shielding and thus significantly increasing the volume occupied within J1T.

2.3 Significant volume occupied in J1T

The WG87-QO will occupy a significant volume within the J1T zone. This volume will be located in the south-east section and at ground level which will obstruct passage during breaks between operation hours. During testing and calibration of the WG87-QO the J1T zone will be restricted to personnel due to the health risks. The advantages of the proposed evacuated waveguide routing include a very small volume occupied by the lines, no obstruction of any passageways, and no limit on access to the J1T zone during periods of testing and calibration of the lines. The evacuated waveguide will be mounted high ($\sim 6\text{m}$) on the wall far from possible

damage or misalignment from personnel working in the zone. The WG87-QO at ground level is much more susceptible to damage and misalignment.

2.4 Cost of the CVD windows and impact on the launcher

One of the motivations in considering the WG87-QO option was economic. The estimated cost of transmitting the power from the MOU output to the torus was less expensive than the WG63 option. However, a significant portion of the cost of the whole transmission system to the plasma was not considered; i.e. the cost of the CVD windows and launcher were not included. The double disk window assembly costs alone are equivalent to the estimated cost of the entire line (~245k\$ for the windows vs. 250k\$ for the line assuming 1Euro = 0.9\$, and including brazing costs). Also, the launcher assembly becomes more complicated having 7 mirrors. This is equal to 2 or 4 mirrors when using an evacuated waveguide system. The added expense of the launcher has not been calculated but was estimated by F. Hoekzema as being of the order of 20 k\$ (Sept. 26, 2001). Applying the same spirit of cost economy, CRPP has investigated the use of an evacuated transmission line (WG31-WG63).

Recently affordable CVD disk have become available for the large diameter waveguides (up to 75mm) purchasable from Prof. Koidl of FhG/IAF, Freiburg. Table 1 lists the price and number of disks per year this company can deliver along with the equivalent cost of the housing assembly unit including brazing and the transmission line costs. Note that the production rate for the 106mm diameter disks needed for the WG87-QO is only 3 disks per year (large diameter disks are required to maintain a low power density on the atmospheric side of the window). This rate is insufficient, an increased production rate can be achieved for higher price disks. The CVD disk price from the DeBeers, which can produce a sufficient quantity, is used for the WG87-QO

	WG31	WG45	WG63	WG87-QO FhG/IAF	WG87-QO DeBeers
Est. cost of line	355 k\$	435k\$ ²	431 k\$	250 k\$ ³	250 k\$
cost of 2 CVD disks	43 k\$	43 k\$	43 k\$	160 k\$	190 k\$
cost of window unit	98 k\$	98 k\$	98 k\$	215 k\$	245 k\$
Disk diameter	75mm	75mm	75mm	106mm	106mm
# of disks/year	10	10	10	~3	---
BaseTotal cost:	453 k\$	533 k\$	529 k\$	~450 k\$	~480 k\$

Table 1 Estimated costs of the four different system including the cost of the transmission system up to but not including the launcher. CVD window prices are from FhG/IAF, Freiburg and DeBeers (for WG87-QO). Note that the production rate of the FhG/IAF disks is not sufficient, price increases if production rate is increased. WG87-QO estimated price would be ~480k\$ + gatevalve for comparison. The pricing of the evacuated lines do not include the second switching system which represents an addition 45 to 65k\$ depending on the diameter.

With the affordable CVD windows for the evacuated waveguide diameters, the equivalent costs of the four systems all fall within ± 40 k\$. The WG45 and WG63 are the more expensive (~50k\$ more than the WG87-QO) but offer higher reliability and ITER relevance. An additional 45 to 65 k\$ can be added to the evacuated lines if an

² Price includes all waveguide items, pumping stations, load, gatevalves and switches but not waveguide supports and microwave detectors.

³ Price includes WG87 section with bellows (100k€), QO section with shielding and switch (95k€), load (57k€, same as WG45), and launcher's added mirrors (25k€ estimated by F. Hoekzema, Sept. 26, 2001) but not gate valve, waveguide supports, and microwave detectors. (Note: 1€=0.9\$)

additional switching system is desired as described in Sec. 5.2. This additional system is not required but adds some flexibility to the transmission line. Depending upon the waveguide diameter chosen, there is no significant cost saving for the WG87-QO as earlier expressed.

The WG87-QO requires the use of the larger diameter disks to insure low power densities on the atmospheric side of the first window. The needed 16 disks would require over five years for production., this is not acceptable within the JET time schedule. The production time can be decreased but this would increase the overall costs or disks can be purchased from DeBeers which also increases the costs of the disks.

In light of the above comments, CRPP saw no advantage in installing the WG87-QO proposal for JET-EP ECRH system. On the contrary, for the equivalent price an evacuated waveguide system could be installed which would provide several advantages without the disadvantages. It seems therefore to us appropriate to put forth this proposal with the aim of increasing reliability, safety and compatibility within the JET environment, while minimizing time delays and costs.

3 General overview

3.1 Description of the line

The proposed routing of the waveguide was chosen to satisfy the following requirements:

- Minimal obstruction of the cranes in J1D and J1T
- Right angle bend either before or after the biological shield (barrier) to allow for neutron shielding
- Minimal number of miter bends
- Minimal line length
- Minimal obstruction of existing structures in J1D and J1T
- Minimal obstruction of passageways in J1D and J1T

The chosen routes have a total of 8 miter bends and an average line length of 71m. The passage within the J1D building follows a similar routing as that shown in Fig. 1. The waveguides leave the MOU vertically downward and pass through the floor to a level of > 2.5m above the ground floor. The lines are directed to the east (not shown on figure 1) and grouped together near the first gyrotron before making the run toward J1T. The small diameter waveguide allows a 100mm separation distance between lines. The waveguide bundle is much more compact than the WG87, this routing is not available to WG87 due to the large clearance needed for the passage of the WG87. Not shown on the drawing are the calorimetric loads which will be positioned to the west of each 'odd numbered' gyrotron. One load will be shared between two gyrotrons which reduces the overall costs and allows conditioning and calibrating of the lines independent of JET operation (see section on Line Calibration).

The routing within the J1T is shown in Fig. 2. The waveguide rises steeply to a level above the remote handling support frame which is positioned on the east wall. At the penetration the waveguides are packed in 2 rows of 4 lines. The waveguide bundle along the interior of J1T is 1 column of 8 lines. The transition is made after entering J1T. The waveguides tilt downward from the east wall to the launcher port. This last section will be dismantled for installation of the remote access unit. The waveguide bundle changes from 1 column of 8 to 2 columns of 4 lines in this section.

The Operator has expressed concern that the shielding needed at the penetration for the WG87-QO options will limit the passage of personnel when the interferometer is extracted. The passage for the WG45 is far from the interferometer and will not restrict the zone. Note: this penetration for the WG45 location is not an option for the WG87-QO, as there is a conflict of space within the J1D zone due to the larger waveguide diameter and spacing distance. The waveguide lines which rise upward after penetrating into J1T will conflict with the platform in the south-east corner of J1T. The Operator views modifying the platform as a minor modification relative to the hindrances related to the access restrictions around the interferometer.

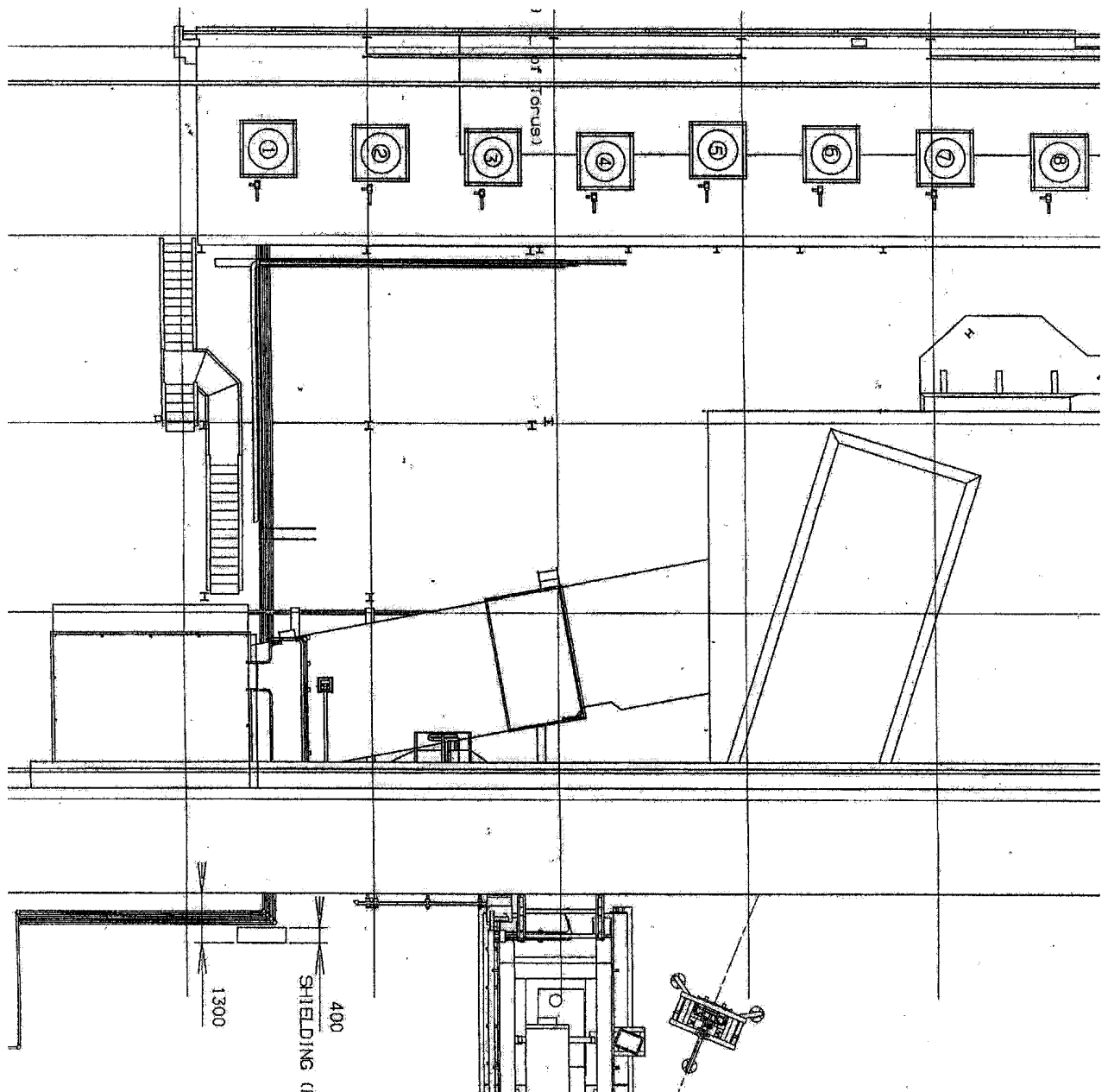


Figure 1 View of the J1D looking from above. The 8 gyrotrons are shown at the top of the figure. The lines leave vertically from the MOU and pass below the floor (not shown) and are grouped near the first gyrotron (from the left). The lines then have a straight run to J1T.

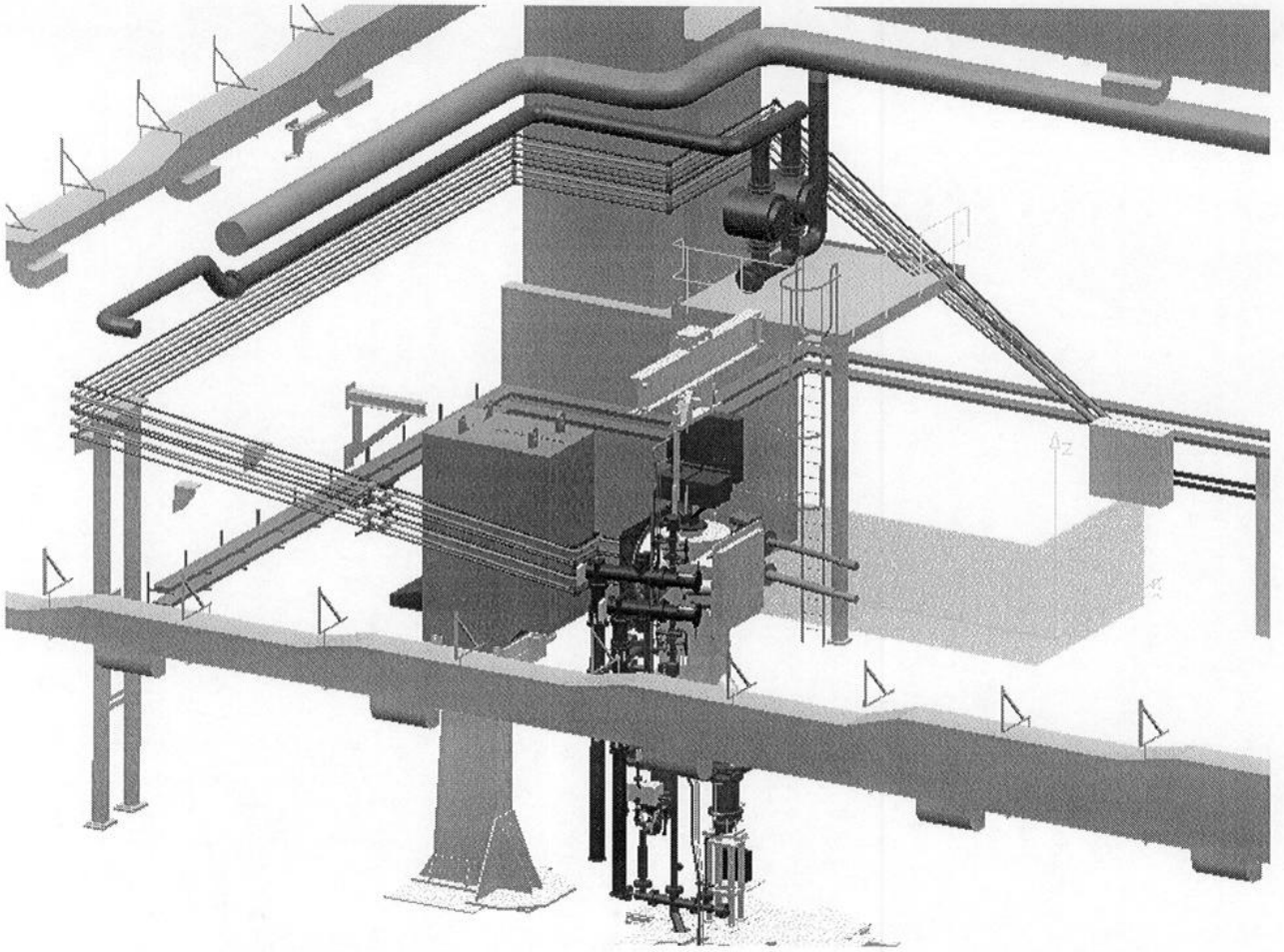


Figure 2 View of the J1T building viewing south-east. The waveguide enters from the south wall then follows around the south and east walls until opposite the launcher port. The last waveguide section which approaches the torus will start in a 8 by 1 array and end up a 4 by 2 array entering the torus

3.2 Accessibility to J1T and J1D

3.2.1 J1D Zone

The only clear passage (east-west) for the crane (when loaded with objects of >2m height) in the J1D building is between the gyrotron towers and the diagnostic platform. The waveguide route was chosen to maintain this region free as shown on Fig. 3.

The waveguide leaves the MOU vertically downward and passes through the floor of the platform. Then the waveguide turns to the east down the corridor. The height of the waveguide allows >2.5m of clearance for the passage of personnel and equipment on the ground floor.

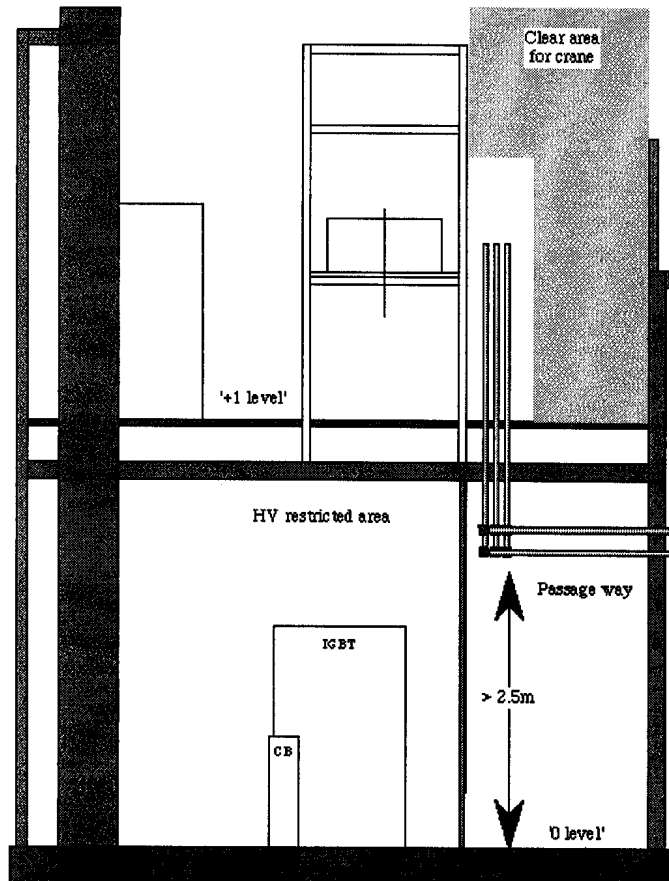


Figure 3 View from the east of the gyrotron platform. The shaded region to the right (north) of the gyrotrons is kept clear so that the crane could pass items between the east and west sides of J1D. Note there will be about 2m between the crane hook and the top of the gyrotron tower. The waveguide will be at least 2.5m above the floor in the passage way (note: only 6 of 8 lines are shown).

3.2.2 J1T Zone

The waveguide passes into the J1T zone near the south-east corner at a height of >2.5m and then bends upward to the east.

The waveguide rises to above 6m and remains at this height along the east wall until inclining downward toward the launcher port. There will be no conflict with either the crane or with the passage of people up until the point where the waveguides leave the wall and descend toward the launcher port (see Figure 2). This last section of waveguide breaching the east wall to the launcher port will obstruct the passage of the crane. No obstruction of passageways will occur at any time within the J1T (and like wise J1D) zone.

of the section of waveguide leaving the east wall and leading to the torus will be the only section of waveguide which is required to be dismantled for full access to the launcher port. The waveguides will be supported from a light weight trestle. The trestle itself will be supported at the east wall and by the hooks used near the torus for the remote handling unit. The procedure for dismantling this section will involve disconnecting the line at either end (at torus and at east wall) and then remove the trestle using the crane. There are 12 bolts to be removed per coupling unit, a total of 16 coupling units or 192 bolts for 8 lines will be removed for dismantling this section of line.

The re-installment will be the equivalent only in reverse order. At CRPP the last section of waveguide is often removed during openings for access and removal of the launchers. The time required for dismantling or mounting the ~3m section of line is about 1 hour. There is no realigning procedure required when remounting the short portion of waveguide. At JET the time required will be more than at CRPP due to the location of the waveguide and the complications associated with working on a larger

machine. There will be no need for realignment of this section since the waveguide couplings are self-aligning and extremely flexible to allow for displacements of the range of 10mm.

The proposed waveguide routing causes no obstruction of passage of personnel throughout the J1D and J1T zones.

3.3 Tritium barriers

The proposed waveguide routing of the WG45 is designed with an option to maintain the two tritium barriers of the JET installation, i.e. torus vessel and torus hall. This section is devoted to a brief description of the possible 'barriers' which could be envisioned.

3.3.1 Torus barrier

At the torus vessel the waveguide vacuum will be separated from the torus vacuum by a double disk window. The region between the two disks can either be pumped via an ion pump leaving the region sealed (monitored via the ion pump current) or pumped and monitored directly for tritium. An all metal gate valve will be placed on the torus side of the window structure for window removal during openings and in case of window failure. The region between the window and the gate valve will need to be accessible for at least rough vacuum pumping and Tritium monitoring before and after each opening of the torus (before dismantling this section for remote access to JET, this section has to be ensured to be Tritium free). The design of the torus window can essentially be the same as proposed for the WG87-QO except a waveguide line would be included. Other options for the window housing unit exists, such as using Helicoflex™ seals which would reduce the cost of the unit and allow replacement of disks in case of damage.

3.3.2 J1D barrier

There are three options for the in-line waveguide barrier at the wall between J1D and J1T:

1. All-metal gate valve
2. Single disk CVD window and an all-metal gate valve
3. Double disk CVD window and an all-metal gate valve

The price estimate presented in the introduction of this text assumed an all-metal gate valve at this barrier. This option is in line with the recent Operator's statement which relaxes the requirement on the CVD window at barrier. To alleviate the fears of 'pumping' tritium from J1T zone and into the J1D zone via the waveguide, the exhaust of the pumps in each MOU would be channeled back into J1T. This limits the worst case scenario of a tritium leak into the waveguide to the confines of the waveguide, MOU, turbo pump and return line (a mass/volume smaller than the equivalent for the WG87-QO proposal). An option to increase the security against tritium leaks exists by using a single or double disk CVD window at the barrier for a relatively small cost with the WG45 proposal. The CVD window can be added at this location for a minimal cost: a single disk for ~46k\$ and a double disk for ~73 k\$ (with Helicoflex™ seals) compared to ~124k\$ and 216k\$ respectively for the WG87-QO.

Normally the waveguide pieces are manufactured in lengths of 2.13m. The wall thickness is 3.8m. In order to avoid drilling a large diameter hole for accommodating the coupling between two waveguide pieces, two pieces can be pre-welded to form a

single 4.0m long piece of waveguide. The required hole diameter per line for the waveguide passage would be ~55mm compared to ~200mm for the WG87. The smaller hole size is an advantage for neutron shielding.

4 Waveguide elements

4.1 Matching Optics Unit

The Matching Optics Unit (MOU) is supplied by the gyrotron manufacturer. It is used to couple the output beam to the waveguide and to adjust the beam's polarization for optimum coupling to the plasma.

There is a risk at the higher power densities under atmospheric conditions that breakdown will occur on the grating mirrors used as polarizers. CRPP has experienced such breakdown on the polarizers, and this was avoided by evacuating the MOU chamber. This option is not used in the WG87-QO. Therefore the beam spot size on the grating mirrors would have to be large to avoid possible break down. This increases the overall size of the MOU in order to maintain the same operation reliability. The WG45 will use an evacuated MOU with much higher allowable power densities on the polarizers. This will reduce the size the MOU.

4.1.1 Universal Polarizer

The universal polarizer is a two grating mirror system which will be included in the MOU. The first mirror has a groove depth of $\lambda/8$, which has the capability of introducing elliptical polarization (β). The second, a groove depth of $\lambda/4$, changes the plane of polarization (α), (α and β are shown in Fig. 4). The polarization changes as a function of the rotation of the two mirrors. For small incidence angles $\beta \approx \phi_1$, and $\alpha \approx 2\phi_2$, where ϕ_1 and ϕ_2 are the rotation angles of the two mirrors. This linear relationship is no longer true for large incidence angles on the grating mirrors. The universal polarizer that CRPP currently proposes has an incidence angle of 20° . The corresponding sinusoidal groove spacing of 1.0mm and depth are 0.7mm and ~1.0mm for the elliptical and plane polarizers respectively. The final design of the grating polarizers is dependent on the design of the MOU which will occur upon signing of the gyrotron contract.

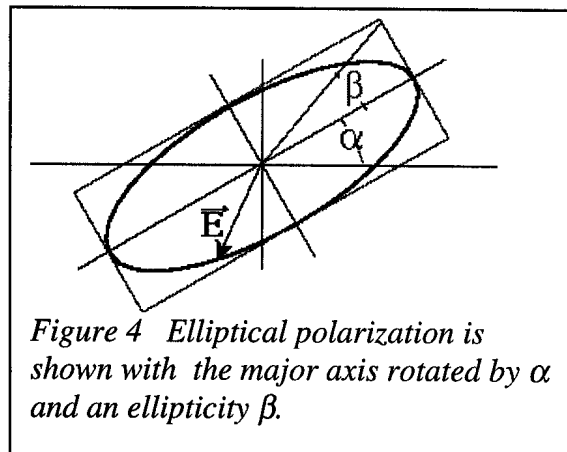
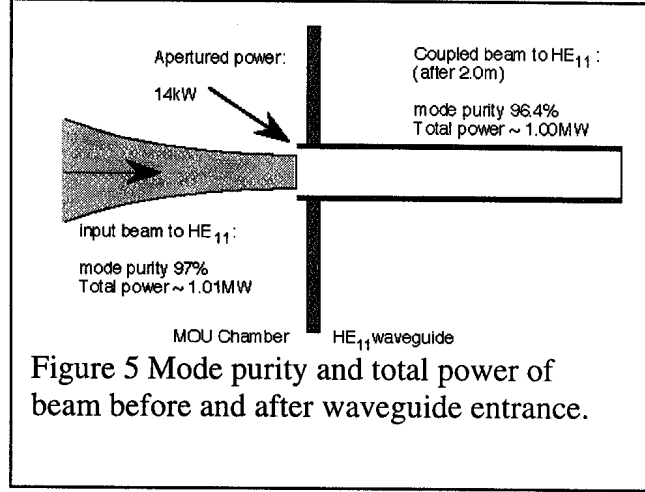


Figure 4 Elliptical polarization is shown with the major axis rotated by α and an ellipticity β .

4.1.2 Waveguide Coupling

The beam coming from the gyrotron is specified to have a mode purity in the TEM_{00} of 97% for optimum coupling into the HE_{11} waveguide. The 3% power in other modes will couple to HE_{1n} type modes, where n is fairly low order but greater than 1. These lower order modes experience low attenuation in the HE_{11} waveguide and a majority of the power in these modes is expected to be transmitted to the end of the waveguide.

When coupling the beam into the HE_{11} mode, 98% of the TEM_{00} is coupled to the HE_{11} mode and 0.6% in the HE_{12} with 1.4% apertured by the edge of the waveguide. The delivered power of the gyrotron is measured after the entrance to the waveguide, so the 1.4% of the power apertured by the waveguide is a hidden loss. Therefore, the delivered power of the 'tube' as measured in the waveguide (1.0MW) is comprised of >96.4% HE_{11} and <3.6% other modes. This is illustrated in Fig. 5. It is important to note that the waveguide is more efficient at transmitting the lower order modes than a quasi-optical system. The finite sizes of the mirrors act as a mode filter for lower and higher ($n \gg 1$) order modes being slightly apertured after each mirror. The WG45 should transmit most of the power in low order modes to the launcher where they will be coupled to the plasma. The higher order modes are highly attenuated in the waveguide. Any power in higher order modes that arrive at the end of the WG45 line will be scattered in the four mirror quasi-optical rather than in the J1T zone (based on the same argument as above).



The operating frequency of the gyrotron shifts during the first 0.5s of the pulse. This shift results in a tilt of the output beam coming from the gyrotron which will be propagated through the mirror system of the MOU and appear at the entrance to the waveguide as a combination of a tilt and offset. The combination of the tilt and offset reduces the mode purity of the beam according to the following:⁴

Power coupled to other modes due to a radial offset Δa :

$$P_{ro}[\%] = 2.14(\Delta a/a)^2$$

Power coupled to other modes to a tilt θ :

$$P_{tilt} [\%] = 0.109(ka\theta)^2$$

where k is the wave number of the gyrotron beam. The power coupled to the other modes cannot be determined until the design of the matching optics unit and its mirrors have been finalized. The maximum power coupled to other modes in the worst case scenario would be <3% for the WG45. The associated losses can be minimized by aligning the beam for optimum coupling after the frequency has stabilized. Thus for the majority of the pulse length (from 0.5 to 10.0s) there will be no increased mode impurity.

The MOU optics can also be designed to translate the tilt and offset of the gyrotron's output beam to a pure tilt at the entrance to the waveguide. This reduces the mode conversion to low levels throughout the pulse length since the WG45 is fairly insensitive to tilts.

⁴ W. Henli et al, Study on ECW transmission lines for NET/ITER, Oct. 1990, EUR-FU/80/90-99

4.2 HE₁₁ Waveguide

4.2.1 Theoretical power handling⁵

2MW operation is well within the safety margin WG45. The calculated maximum field strength for 2MW is less than 30kV/cm compared with > 200kV/cm needed for breakdown within a waveguide at pressure of $\sim 10^{-5}$ mbar.

4.2.2 Present experience

The WG45 is in principle a new waveguide diameter. However, there are several fusion labs around the world which have experience with evacuated WG31 type transmission systems at high power levels. Representatives of these labs have been contacted in preparation of this proposal. Table 2 is a summary of their experience with the WG31. Note that JT60-U and LHD currently use in-line CVD windows in the 31.75mm waveguide. LHD is also in the process of testing the window housing assembly produced by GA using Helicoflex™ seals rather than brazing. A recent data point for JT60-U has been added at 0.8MW for 1.0s. This corresponds to the equivalent to 1.6MW power levels for the WG45. TCV is also given as a reference.

Device	Waveguide Diameter	Power pulse length	# of miter bends	Line length	Theoretical losses	Measured losses
JT-60U	31.75mm	0.6MW-3s	9	53m	14%	19% ⁶
JT-60U	31.75mm	0.8MW-1s	9	53m	14%	20%
DIII-D	31.75mm	0.7MW-3s	6-12	50-95m	$\sim 16.5\%$	$\sim 16.5\%$ ⁷
LHD ⁸	31.75mm	0.6MW-3s	10	65m	7.9%	
TCV	63.5mm	0.5MW-2s	5	30m	3.6% ⁹	4.1%

Table 2 List of the current labs using the WG31 waveguide is shown with a description of each system and the calculated and measured efficiencies where possible. Note, the WG63 system of TCV is included.

4.2.3 Waveguide losses

The losses associated with the HE₁₁ waveguide can be divided into two groups: ohmic and higher order mode conversion arising from misalignments and bending of the waveguide. These losses will be treated on an individual basis for the three types of waveguide possibilities.

The attenuation per 100m of waveguide is shown in the Table 3 for three waveguide diameters. Note that WG87 refers only to the waveguide section of the WG87-QO option and not the whole line.

⁵ Calculation provided by John Doane of General Atomics using information in A.D. MacDonald and S. J. Tetenbaum, High frequency and microwave discharges, in Gaseous Electronics vol. 1, Electrical Discharges, Hirsch and Oskam, eds. Academic Press (1978).

⁶ The high measured losses in the JT-60U is attributed to a 'snaking' of the waveguide alignment. This periodic misalignment has significant mode conversions. JT-60U is in the process of re-aligning the supports for improved transmission.

⁷ DIII-D performed cold test measurements of all components, these components agreed with theoretical calculations.

⁸ LHD uses mode converter miter bends in their transmission line. LHD plans on measuring the line losses near the end of September.

⁹ Only ohmic attenuation and percentage of power in higher order modes, there is an $\sim 4.7\%$ in lower order modes.

	WG31	WG45	WG63	WG87
Attenuation dB/100m	0.24	0.08	0.03	~0.01
Average length	71.2m	71.2m	71.2m	29.5m
Attenuation in line	3.9%	1.3%	0.5%	.07%

Table 3 An estimation of the expected losses related to the ohmic attenuation in the waveguide for the three different waveguide proposals. Note that the WG87 is only for the length of line in the J1D zone.

The larger diameter waveguide has a much lower attenuation than the smaller waveguide as seen from the above. However, this advantage is counteracted by the mode conversion which occurs from bending of the waveguide either from misalignments or sagging due to gravity. As an example of the mode conversion which could occur in a section of waveguide, a section of 7.3m of waveguide is taken with fixed supports on either end with the center allowed to sag as a result of gravity. The resulting sagging and associated mode conversion due to the bending of the waveguide is shown in Table 4¹⁰:

	WG31	WG45	WG63	WG87
Sag	16 mm	10 mm	4.7 mm	2.6 mm
ΣP_c	0.04%	0.2%	0.8%	2.4%

Table 4 The advantage of the low attenuation in the large waveguide diameter is counterbalanced by the increased mode conversion in waveguide sagging or bending. The WG45 is interpolated from the 31.75 and 63.5mm waveguide calculations.

Despite the large sag (10mm) in the WG45, the resulting mode coupling is negligible 0.2%. However, the WG87, which sags only 2.6mm, has an order of magnitude higher amount of mode conversion. The sensitivity to sagging requires the supports of the WG87 to be placed much closer together and consequently a line of ~1/2 the length will require roughly the same number of supports.

However, closer spacing introduces a second problem and that is support misalignments. The same calculation above can be restated as an example of the alignment need for each of the waveguide diameters. If supports are placed at half the distance as above and the supports are misaligned by the same distance as the sag in the above example, then the resulting mode conversion due to the misalignment will be identical to that shown in the previous table.

This demonstrates the increased care needed in aligning the supports for the WG87 in order to maintain a high mode purity in the transmission line. The resulting mode purity in the realized line will depend on the support spacing, line length and alignment accuracy. It is not possible to estimate accurately the losses without a good knowledge of the true line lengths. The strongest conclusion that can be drawn is that for a given simple support system, the WG45 will have significantly lower mode coupling due to bending and misalignments than the WG87 and that the hidden costs in precision supports and time invested can be much more significant for the WG87 than the WG45. CRPP used a relatively simple low cost laser set up to align the WG63 supports and miter bends to within $\pm 2\text{mm}$ over distances of 20m.

There will also be a slight misalignment and tilt at each joint between waveguide sections. These losses are negligible if the coupling units are machined with

¹⁰ 88.9mm rather than 87mm was used. These calculations were provided by Tim Goodman, CRPP.

precision tolerances. Spinner/GA have demonstrated that their couplings introduce negligible mode conversion at the waveguide joints. The greater number of joints also increases the potential for mode conversion. Spinner/GA's waveguides are made in 2m section while the WG87 contains a proposal for 1m sections.

4.2.4 Total HE_{11} associated losses

The total losses associated with the waveguide include those losses described in waveguide section and are listed in Table 5:

	WG31	WG45	WG63	WG87
Input beam	3.6%	3.6%	3.6%	3.6%
Ohmic attenuation	3.9%	1.3%	0.5%	0.07%
Sag and misalignment	~0%	~0%	~0%	???
Total losses	7.5%	4.9%	4.1%	3.7%

Table 5 Total estimated losses associated with the coupling of the beam in the waveguide and propagation along the proposed lengths. Note the mode coupling in the WG31 and WG63 will be negligible, this may not be true for the WG87 which requires much more precision in alignment. Note the WG87 is only about half the length of the either WG31 or WG63.

Note that losses for the WG31 to WG63 are for 71m of line while the WG87 is for ~29.5m. Also the losses due to sagging and misalignment of the WG87 can only be estimated once the spacing and alignment precision is known.

4.3 Miter Bends

A significant portion of the losses associated with the WG45 line is from the miter bends. These losses can be reduced by either replacing the flat mirror with a phase corrected mirror or introducing mode converters before and after the miter bend. A summary of the three choices and their costs are shown in Table 6. The cost of the waveguide can be optimized either on the basis of delivered power or on overall costs. The flat mirrors offer the lowest cost with the highest loss, the phase corrected mirrors offer medium cost and losses while the miter bends with mode converters are the most expensive yet have the lowest losses. All three options are possible but for this proposal only the phase corrected miter bend mirrors will be considered.

	Flat mirror	Phase corrected	Mode converter
Miter bend type	A	B	C
Ohmic ¹¹	0.15%	0.15%	0.15%
Mode conversion	0.8%	0.55%	0.2%
Total losses/Bend	0.95%	0.7%	0.35%

Table 6 Comparison of the three type of miter bends available for the WG45. The three options allow a choice between reaction of losses versus reduction of price. This proposal will consider the phase corrected mirrors. How is the cost evolution assuming 1 for the flat mirror?

The losses associated with the two waveguide diameters are shown in Table 7:

	WG45	WG87-QO
Power loss/bend	0.7%	0.35%

¹¹ Assumed for worst polarization and 'realistic' surface conditions.

# of miter bends	8	4
Miter bend losses	5.6%	1.2%

Table 7 Comparison of the losses associated with the miter bends for the two different waveguide diameters.

The power loss on each miter bend is a sum of the ohmic and mode conversion losses. The ohmic losses are estimated at 0.15% for each of the waveguide diameters (average between E and H plane bends). The remaining losses are associated with the conversion to lower (1/2) and higher (1/2) order modes within the miter bend. Half of the power in the higher order mode is reflected and the other half directed forward.

The power monitor miter bend will have equivalent losses as the miter bends described above. The power monitor allows the monitoring of the forward and reflected power in the waveguide. It can be located either as the first or last miter bend in the line. The power monitor will be cross-calibrated with the calorimetric measurements of the power delivered at the entrance to the launcher.

4.4 Quasi-Optical Propagation

The principal losses for the WG45 lines are the waveguide attenuation and the miter bends as shown above. The WG87-QO line encounters these losses as well as the losses within the quasi-optical section of the line. This section is devoted to provide an estimate of the losses which can be expected for the quasi-optical section of WG87-QO. These estimates are to be in the overall transmission losses for comparison purposes and are listed in Table 8. Three main losses are included in the estimate: ohmic losses on the mirror, aperturing of the beam on each mirror and atmospheric absorption of the beam in free space. This estimate does not include losses associated with mirror deformation due to thermal expansion or misalignment of the mirrors.

	Losses	#	Σ losses
Mirror-Ohmic	0.15%	8	1.2%
Diffraction		8	1.1%
Cross Polarization		8	1.0%
Atmospheric	~0.6dB/km	~70m	1.0%
		Total:	4.3%

Table 8 List of the associated losses in the quasi-optical section of the WG87-QO line obtained from presentation of Sept. 28, 2001, the atmospheric absorption has been added by CRPP. Note this list does not include all losses such as losses associated with misalignment and distortion of the mirror surface due to thermal effects.

4.5 Total Transmission Losses

The total losses associated with the potential transmission lines are summarized in Table 9.

	WG45	WG87-QO
HE11 losses (Sec.A, B)	4.9%	3.7%
MB losses (Sec. C)	5.6%	1.2%
QO propagation (Sec. D)		4.3%
Total losses¹²	10.5%	9.2%

Table 9 .List of the total losses and mode conversion to be expected for the different proposals. Note that the quasi-optical section is a minimum estimated value..

Note that the above table has no estimation for the coupling to lower and higher order modes due to misalignment which, as shown in Sec. III.B.3., increases significantly with waveguide diameter. Also, the majority of the power converted to lower order modes is not attenuated in the waveguide but is propagated to the waveguide end. A significant portion of the lower order modes can be transmitted to the plasma if the number of mirrors between the end of the waveguide and the plasma is small and if the mirrors are of the order of four times the beam spot size on the mirror. Increasing the number of mirrors or decreasing the size of the mirrors tends to filter out the lower order modes. The lower order modes typically are HE_{1n} type (with small n) with the majority of the power in the central lobe. This power will propagate to the plasma with a similar divergence as the principal HE_{11} mode (converted to TEM_{00} at the waveguide aperture).

The fraction of power in lower order modes that will be transmitted to the plasma with a divergence similar to the HE_{11} mode is difficult to estimate. Measurements of the transmission efficiency of the waveguide lines and launcher at CRPP have shown that most of the power in the forward directed lower order modes is transmitted through the line and QO launcher (4 mirrors). The theoretical efficiency of the lines (5 miter bends, ~30m of 63.5mm waveguide) is 91.6% with 3.7% in ohmic, higher order or reflected modes and 4.7% in forward directed, lower order modes. Calorimetric measurements of the line and launcher resulted in a measured efficiency of 95% averaged over the 6 lines. In order to have 95% efficiency, over 70% of the power in the lower order modes had to be transmitted through the line-launcher and with a similar divergence angle as the TEM_{00} to be coupled into the load positioned after the launcher.

The possibility exists that ~70% of the lower order modes in the WG45 will be transmitted to the end of the line. The WG87-QO will have a lower efficiency in transmitting these modes due to the mode filtering nature of the QO systems described previously. If we assume that ~70% of the lower order modes will arrive at the plasma for the WG45 and 0 to 70% for the WG87-QO, then the total transmission efficiency will as shown in Table 10:

	WG45	WG87-QO
Ohmic portion	2.5%	4.92%
High order and Reflected modes	2.2%	0.4%

¹² Losses due to other waveguide components are small relative to the miter bends and waveguide attenuation.

Low order modes	5.8%	4.0%
Estimated fraction of lost forward power modes ¹³	0.3	0.3 – 1.0
Est. % lost of forward power modes	1.7%	1.2 – 4.0%
Est. Total losses	6.4%	6.3 – 9.3%

Table 10 Comparison of the estimated losses of the different lines with partial transmission of the lower order modes. The percentage of power in lower order modes transmitted is estimated from measurements taken on the WG63 lines at CRPP.

Note the above table assumes the waveguides will transmit a greater fraction of lower order modes to the launcher than the QO system. If this estimate is reliable than the WG45 will have an equivalent transmission efficiency to the WG87.

4.6 Temperature rise in Waveguide

The waveguides will be heated as a result of the ohmic losses and the absorption of lower and higher order modes along the length of each line. There are two possible risks involved with the heating of the waveguide. First the lines may overheat and be damaged if they are not sufficiently cooled. The waveguides can be baked to 150°C which is a reasonable limit to the allowable temperature of the waveguides. Also the lines will expand. The expansion of one line will bend the previous (or following) line and cause an increase in the power coupled to higher order modes. The supports are designed to allow up to a 10mm deflection over a support length of 3.5m (as was shown in the previous example) which corresponds to 0.2% mode conversion (the supports at the torus will be treated differently). For the proposed WG45 design there will be one line ~19.5m in length and fixed on one side by the barrier between J1T and J1D. With a thermal expansion of the waveguides of 23×10^{-6} , a 35° temperature rise would result in a 15.7mm expansion, ΔL , of this line segment. The resulting deflection will be split between the two adjacent legs i.e. ~8mm on each leg.

The rise in temperature of each line is calculated assuming all of the lower and higher order modes are absorbed in the waveguide and that the lines are cooled by free convection to air¹⁴:

$$\Delta T = \frac{Q'}{h \cdot A'}$$

Where ΔT is the temperature rise, Q' is the average heat flux per meter of waveguide, A' is the surface area of one meter of waveguide and h is the heat transfer which averages between 5 to 25watts/(m² K). Note the above assumptions concerning the absorption of all modes is a worst case scenario. Assume that all lost power is absorbed in the lines except the ohmic power absorbed in the miter bends. The resulting temperature rise and expansions are given for the two proposed waveguide diameters in Table 11.

	WG45	WG87-QO
Power absorbed in line	93kW	48kW
Q' [W/m]*	11.0	16.6
ΔT	14.0	10.6
ΔL [mm]†	6.3	4.7

Table 11 The expected thermal expansions for a 19.5m length of line. This line length represents the longest section of line associated with the movement of one end of the line keeping the other end fixed.

¹³ Estimated fraction of transmitted lower order modes is based off of measurements performed at CRPP.

¹⁴ Provided by John Doane.

* Q' was calculated assuming the average line length of 71m was for WG45 and 29.5m for WG87 and a 1% duty cycle.

† A 20m section is used for both lines.

The above calculation is for the worst case scenario, full absorption of higher order modes and the lowest heat transfer to air. Note the expansion for the WG45 is less than the 10mm which would correspond to a 0.2% mode coupling. However, special attention would need to be given to the WG87 line to compensate for the 4.7mm expansion such as in-line bellows or waveguide cooling. Recall from Table 4, a 2.6mm shift resulted in a 2.4% of the power coupled to higher order modes. The expansion above will result in even higher power coupled to higher order modes. To avoid this the WG87 line will need in-line bellows. The WG45 will have negligible levels of power converted to higher order modes without the use of in-line bellows.

5 Additional Waveguide elements

5.1 CVD diamond window

The competitive prices of the WG45 over the WG87-QO is due to the CVD disks used for the window assembly. The WG87-QO also requires a larger diameter and a thicker disk than the WG45. The lowest price CVD disks with good RF properties ($\tan\delta < 1 \times 10^{-4}$) are available from Prof. Koidl of FhG/IAF, Freiburg and are given in Table 1.

The base design of the CVD window housing uses the proposed assembly from FZK. Costs shown in Table 12, note the WG87-QO price is based on the quote from DeBeers, the production rate of FhG/IAF, Freiburg is not sufficient for the JET-EP ECRH project time schedule, 3 disks per year (Note: 2 106mm disks from FhG/IAF, Freiburg are ~165k\$).

	WG45	WG87-QO
Two windows [k\$]	49.8	189.8
Brazing of two windows [k\$]	25	25.0
Housing unit [k\$]	~25.0	~30.0
Price per assembly [k\$]	99.8	244.8

Table 13 Summary of the costs associated with the window housing unit.

A second option would use Helicoflex™ seals rather than brazing. This option reduces the cost of the assembly and allows an easy way of replacing the CVD disks in case of failure. This method is already in use on LHD and has achieved 0.39MW for 0.5s (operation started only recently) with the planned extension to near 1.0MW levels. This system will not be presented in detail here but will be noted as a viable alternative to the brazed disks. The full assembly has already been designed and can easily be adapted into this proposal upon acceptance.

5.1.1 Resonant cavity between windows¹⁵

During the MM22 meeting there was concern that two windows in a waveguide line would create a cavity. The CVD disks have a nominal tolerance of about $\pm 0.02\text{mm}$. A deviation of 0.018mm out of 1.11mm corresponds to a frequency deviation of

¹⁵ Information was provided by John Doane

1.6% and results in $\sim 1\%$ reflection from a diamond window. A 1% reflection from each window makes a cavity between windows with $Q \ll 1$. The total round trip interference (echo) with the main wave is $-20-20 = -40$ dB in that case. For a single such echo, the corresponding variation in the transmission versus frequency is $\pm 2\%$. So a 1% reflection corresponds to the extremes of the tolerance. All window housing assemblies will be low power tested before use. Note, only a single window system is used in this base design according to the requirements of the Operator. Therefore the equivalent problem exists as well with the WG87-QO option. If a second window assembly is to be added at the barrier between J1T and J1D, then the added risk of reflections can be avoided by: pre-testing the window assemblies and possibly tilting the disks to avoid cavity effects.

5.1.2 Present experience

There are two labs using CVD in-line windows, JT-60U and LHD. The following is a description of the power and pulse lengths that have been achieved through the two systems.

*JAERI, JT-60U*¹⁶

The maximum power and pulse length achieved on the JT-60U ECRH system is 0.6MW-3.0sec or 0.8MW for 1.0s. The later corresponds to ~ 1.6 MW in the WG45 window assembly. The limits of the performance are the gyrotron output power and transmission losses, not the transmission capability of the windows. For an undefined reason, the gyrotron power is limited to 0.7-0.8MW at JT-60U.

*NIFS, LHD*¹⁷

LHD has a 31.75mm CVD window on the stellarator side of the transmission line. The power at the window will be 600kW for 3s. Transmission experiments will occur during the end of August and operation on LHD is scheduled starting near the end of September. To date 390kW has been transmitted through the window assembly for 0.5s.

5.2 Load/Switch

A switch-calorimetric load will be required somewhere along the length of the line. The load is useful for :

1. Conditioning/testing the transmission line at the start of a campaign period
2. Power measurement of the output beam
3. Conditioning the gyrotron at long pulse operation
4. Short pulse operation of the gyrotron at the start of each day for establishing correct cathode heating current

Current experience with the evacuated waveguide lines have not required the conditioning of the lines before a campaign period. Likewise, current generation of European fabricated gyrotrons no longer require conditioning before an operating day nor after an 'arc' event with in the gyrotron. The preliminary proposal of the WG45 suggested placing a switch near the output of each gyrotron with one end of the switch directed to a shared load between two gyrotrons.

The option of putting the load at the end of the line would permit the testing of the whole assembly (gyrotron-MOU-line) up to the torus window before each operating

¹⁶ Communication with Koji Takahashi, JAERI

¹⁷ Communication with Shin Kubo, LHD

day. The JET operator prefers the reduction of 'mass' which could be irradiated within the J1T zone.

Upon discussions during the MM23, a second switching unit in the transmission line was conceived which would allow all of the above options while keeping the loads near the gyrotrons. A switch will be placed at the end of each line which would redirect a beam into a second transmission line and return down that line back to the load. The concept is illustrated in Figure 6. The cost of this option adds about ~45k\$ (WG31), 55 (WG45) or 65k\$ (WG63) to the total cost of the line. The 'base' design would remove switches C and D while still maintaining the one load shared between the two gyrotrons. This would still allow conditioning and calibration of the gyrotrons and lines with open access to J1T.

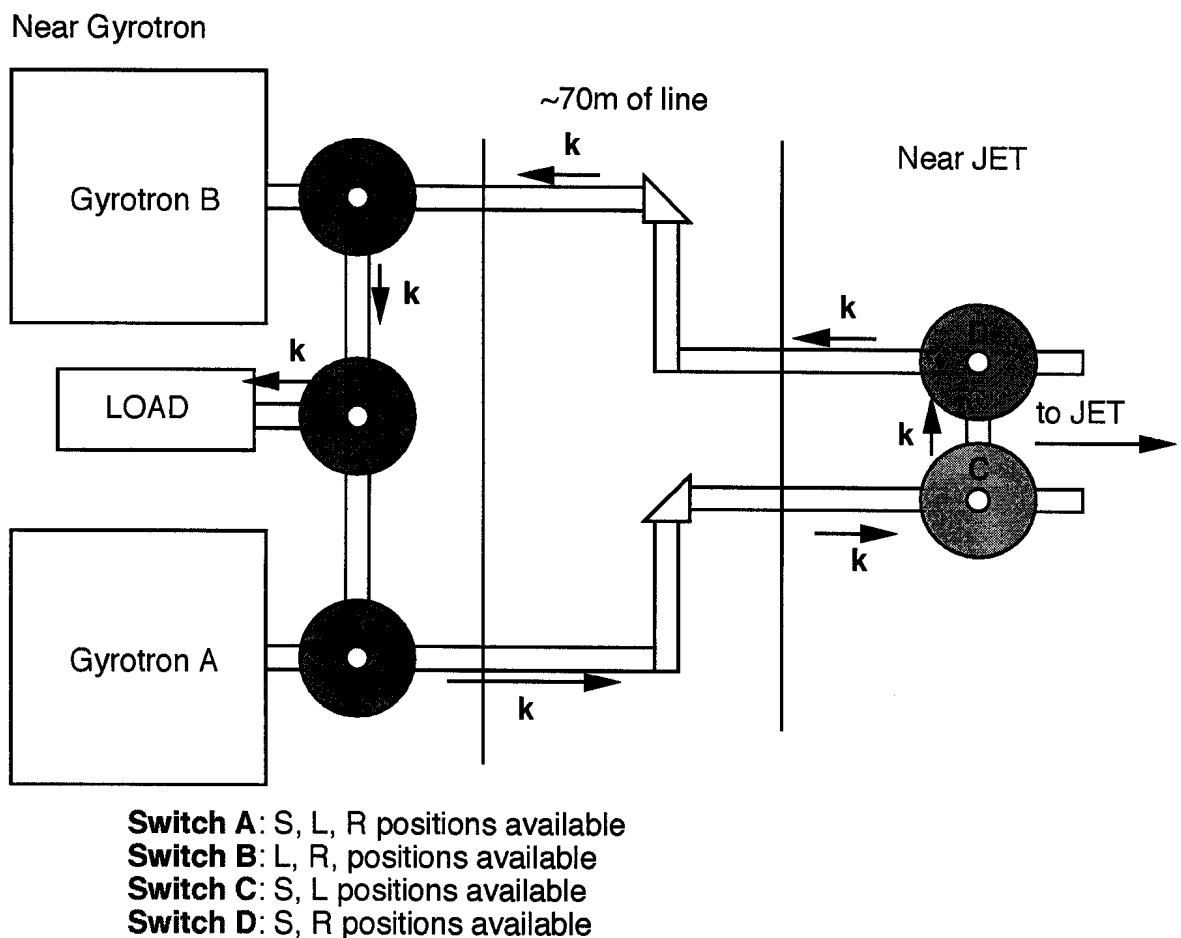


Figure 6. Proposed switch configuration which allows the operation of each gyrotrons into the torus (red path), directly in the load(blue path) or via two lines and then into the load (green path).

This design increases the number of switches per two lines by 3 (~66k\$) but reduces the overall cost by one load (~100k\$) at the same time allows full flexibility for conditioning gyrotron and line.

At present there are two 1MW loads available, these are shown in Table 14.

	Price	Length	Flow
GA	102k\$	~2.6m	6l/s
Calabazas	~160k\$*	~2.0m	12l/s

Table 14 Prices of 1MW loads available of the market.

* The price estimate for the Calabazas load is from 1998.

5.3 DC Break

An in-line DC break with isolation voltage of 5kV will be located at either side of the transmission line. The line will be both isolated from the gyrotron and the tokamak. Stray microwave radiation emitted from the DC break is $\leq 5\text{mW/cm}^2$ at a distance of 3cm the total radiated power will be $\sim 1.9\text{W}$.

5.4 Pump out T

The waveguide will be pumped via two pumping systems: MOU and an in-line pump out T. The WG31 lines on DIII-D have up to 80m of waveguide between the pump out T and the MOU and have experienced no breakdown problems at the maximum power to date of 0.7MW. The maximum line length at JET is 80.7m, with the pumping T positioned about 2/3 the distance down the line leaving a maximum distance of 56m between the pumping T and the MOU. If a second double disk CVD window is added at the barrier, the MOU would pump the line section within the J1D. The maximum length between the MOU and the window is 38m which is equivalent to the 80m between pumps at DIII-D. Note with the WG45 the pumping conductance will allow longer runs than the WG31.

The WG31 line at DIII-D is equivalent to that proposed for JET. The DIII-D line will be $\sim 90\text{m}$ in length and pumped via the MOU and one in-line pumping station. GA has estimated that 6 hours will be required to pump this line before beginning microwave operation¹⁸.

The pump out T will require only a small turbo pump. The ideal pump would be a dry-vac turbo pump which is fairly compact and requires no additional roughing pump. The quoted cost of the entire pumping station including gauges and controllers is 8.9k\$.

5.5 Support structure

CRPP already has drawings for the support structures needed for the mounting of the WG63 line. These drawings can easily be modified to accommodate the WG45 as well as adapted to the applications of JET. The supports used at CRPP were made in-house. Drawing of the CRPP support could be provided upon request. (In this purely technical document I do not feel that it is appropriate to say that we are ready to take the job)

6 Costs

The cost of the transmission line is estimated from a quote received from GA. The estimate is shown in Table 15, which uses the precise line length and items from the

¹⁸ H.J. Grunloh et al, Design and Analyses of Transmission Lines for the 110GHz ECH Upgrade to 6 MW for DIII-D, Nov. 1999, GA Report GA-A23288

current routing design. The costs and number of elements for the WG87-QO is taken from the presentation of Sept. 27, 2001. All values are in US\$ (1€=0.9\$).

	WG31	WG45	WG63	WG87-QO DeBeers
Est. cost of line	244 k\$	299k\$	270 k\$	191 k\$
2 gate valves	60 k\$	90 k\$	90 k\$???
Load (1 per 2 gyros)	51 k\$	51 k\$	51 k\$	51 k\$
cost of window unit	98 k\$	98 k\$	98 k\$	245 k\$
Switching system	45 k\$	55 k\$	65 k\$	9 k\$
UpperTotal cost:	498 k\$	588 k\$	594 k\$	>480 k\$
Lower Total cost:	453 k\$	533 k\$	529 k\$	>480k\$

Table 15 Summary of the total costs of the four different proposals. The prices for the WG45 include all line items to be purchased including load and switching systems. The equivalent load is included for the WG87-QO. The Lower Total cost removes the switching system described in section 5.2 while maintaining only one load per two gyrations.

The price of the load (~102 k\$) is included in this cost estimate. The switching system proposed with the WG87-QO was not included in the above estimate. The cost of the equivalent switching system for the WG45 is ~55k\$ per line (In Table 15 the cost for WG45 includes the switch which redirects the power from the end of the line back to the load near the gyrations). If this cost was removed while still maintaining one load per gyrotron the line prices would reduce to 453 k\$ for WG31, 533k\$ for WG45, and 529k\$ for WG63. The WG63 in this case is cheaper than the WG45 because the design work has already been completed and flat mirrors would be used (savings of ~12k\$).

The Table 15 offers a summary of the costs and losses of the two transmission line options. The above price for the WG45 includes all waveguide items and pumping stations for both the line and MOU. Items such as cabling, fiber optic cables, microwave detector diodes, etc. have not been included but will not effect the total price significantly. The costs of the supports are not included in this document. The supports themselves are extremely simple and can be made in-house. The estimate is also sensitive to conversion rate fluctuations between the US \$ and the .

7 Launcher

7.1 Description

The current launcher design has a 7-mirror assembly. This could be greatly simplified by continuing the WG45 into the launcher port up until the 4th or 6th mirror. The Gaussian optics of the last two to four mirrors could be designed to obtain the same order of power density in the plasma. The relatively small size of the waveguide would reduce the space needed for the entrance of the beam into the launcher chamber. There is a potential that the KN3 diagnostic could then be placed at a closer radial location (this would also require a modification of the current actuator design which appears feasible).

Ben Elzendoorn, FOM, has proceeded in modifying the launcher with the waveguide inserted up to the fourth mirror, see Figure 6. The current design uses WG31 option at the input with an uptaper after the miter bend. The uptaper is not needed and will be removed on future designs.

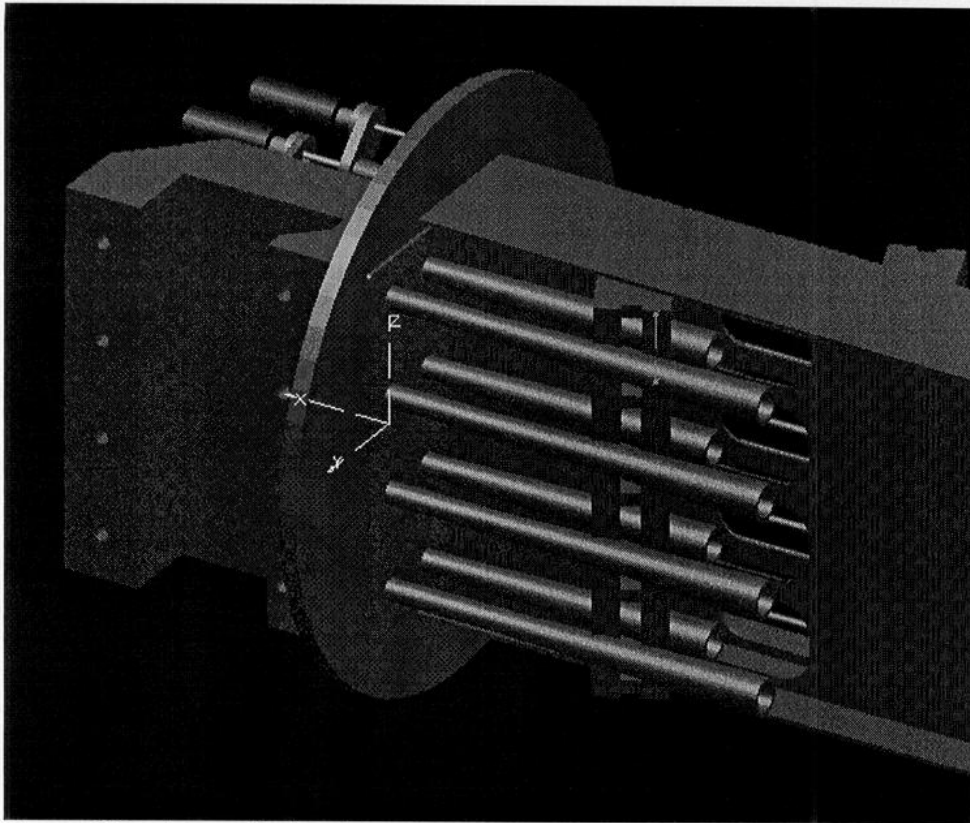


Figure 6 Design of the launcher provided by Ben Elzendoorn. The waveguide inserted into the launcher simplifies the design and reduces the number of internal mirrors.

It is advantageous to have the internal mirror optics to be compatible with two frequencies (113.3GHz and 170 GHz). The WG87-QO has an advantage in that the external mirror can be changed to allow similar beam propagation through the launcher. With the WG45 option the first mirror after the waveguide aperture will have a smaller beam spot size at the potential 170GHz frequency. This will result in higher power density and higher thermal loading on this mirror. With the choice of correct mirror curvature, loading on succeeding mirrors can be nearly equivalent for the two frequencies. The thermal loading of the first mirror will not exceed that of the mirrors of the miter bend and with proper cooling there will be no threat of exceeding thermal limits.

There was concern of breakdown in the section of waveguide due to large power density in the waveguide. With the current design the end of the waveguide is recessed far back into the launcher port. At this location there is no fear (based on experiences with on other tokamaks) of breakdown in the line. A second concern was the possibility of breakdown in the line at other resonant surfaces. DIII-D was cited as having problems with break down in their internal lines. Aside from the case when the shutter at the end of the launcher was partially closed during operation (resulting to damage to the waveguide), there has been no damage to the waveguides at DIII-D on their outside launchers. The third harmonic resonance is located at their waveguides for 110GHz. The 60GHz low field side line/launcher did not encounter breakdown problems either. This launcher had comparable power densities to the JET line with the second harmonic in the waveguide.

TCV operates routinely with the third harmonic resonance on the last mirror. Although the power densities are lower ($\sim 1/4^{\text{th}}$) this mirror is located very close to the plasma ($>5\text{cm}$).

There was a remark that DIII-D has observed light near their launcher/line. The pressure level near the launcher is estimated to be around 10^{-4} to 10^{-5}mbar . There has been no degradation of beam quality during operation. To their knowledge there is no 'light' in that region.¹⁹

8 Misc.

8.1 Torus displacements²⁰

The torus will move due to heating and disruptions. The torus is nominally heated to 320°C which corresponds to a displacement in the region of the launcher port of $\sim 18\text{mm}$. During a disruption the largest displacement of the torus is 16mm (6MA 4T) but since operations are limited to 5MA, the displacement is 13.5mm . The displacement is a concern for ECRH transmission lines only due to potential damage of the waveguides due to bending. The window unit will be designed to transmit the forces from the torus displacement to the window housing and transmission line and avoid stress to the CVD disks. Since the beam will be shut off during disruptions, there will be no concern for mode conversion losses arising from waveguide bends.

Note the Operator desires the displacement tolerances to be increased to 25mm for both heating and disruptions. Since JET operates 'hot' the waveguide will be aligned to the torus when the vessel is hot. This will insure minimal losses as well as reduce the displacement to $\pm 25\text{mm}$ rather than 50mm .

If the section of WG45 leading to the launcher is only 1.5m long, the torus could be displaced by 50mm before plastic deformation occurs. The last leg leading to the torus will include a miter bend (reduces stress by $1/2$) and with approximately 1.5m on either end of the miter bend free (reduces stress by $1/4$). The resulting stress on the waveguide will be reduced by a factor of 16 since the waveguide will only experience a 25mm movement.

The 7G force which may be submitted to the waveguide during a disruption translates to a force of 0.6MPa on the waveguide. This is relatively small since the forces for plastic deformation are of the order of 260MPa ²¹.

8.2 Power Calibration

The delivered power to the launcher can be monitored during a pulse via the power monitor miter bend (PMMB) and via the body voltage (V_b). In both cases the delivered power will need to be measured calorimetrically before use of each gyrotron. With the switch configuration described in Sec. V B., it is possible to perform the power calibration along with conditioning of the line at any time. Since the calorimetric loads will be accessible to the beam either directly after the MOU or after two lines, the gyrotron or the lines can be conditioned at any time. This implies that there will be no restrictions to personnel into J1T at any time during conditioning or calibration. This is not the case for the WG87-QO which will not permit the operation of the gyrotrons through the line with

¹⁹ Communication with John Doane and Ron Prater.

²⁰ Valeria Riccardo, JET provided the displacement values

²¹ Calculations provided by John Doane, GA.

personnel access to J1T. The WG45 offers a significant advantage over the WG87-QO to the JET operation with this feature.

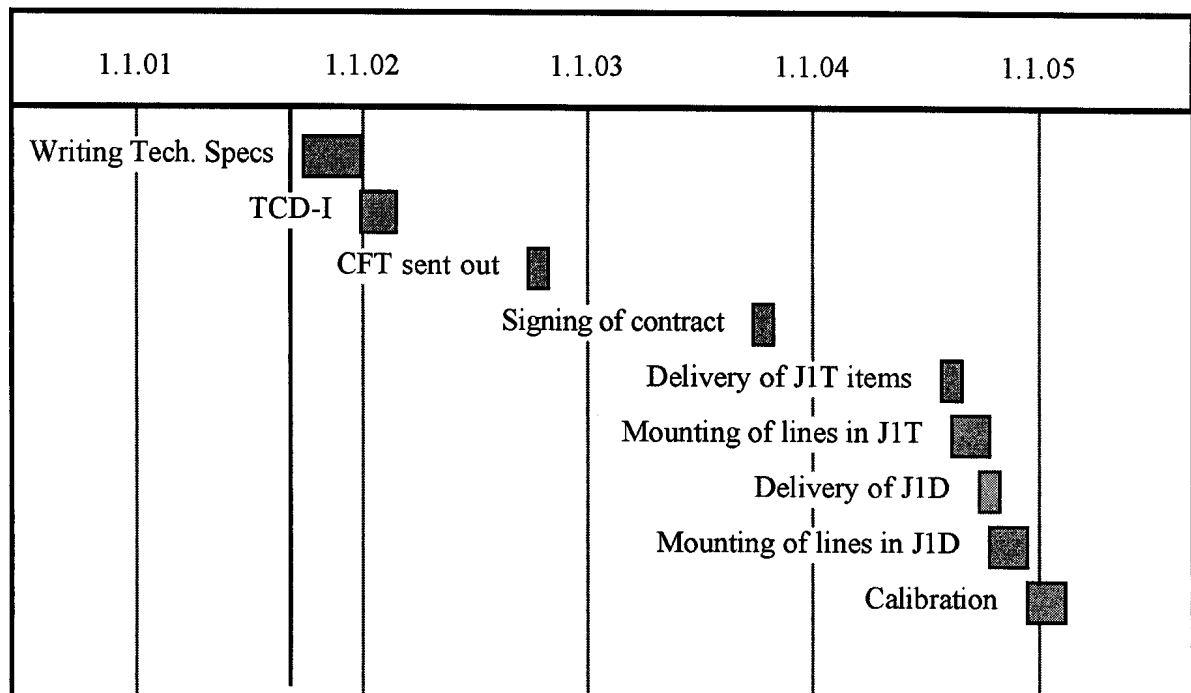
8.3 Polarization Calibration

The polarization at the end of the line will be rotated relative to the input polarization due to the two non-horizontal sections of waveguide in the J1T. A cold test calibration of the MOU and a mock line assembly is to be performed to account for the above rotation. The related work does not have to be performed on the transmission line in-situ but can be done on small prototype line with similar tilts as the true line.

9 Schedule

The following chart is an estimate of the time required from preparing the call for tender to the first operation of the gyrotron into the launcher. The Table considers only the transmission line and no other time constraints such as the launcher or procurement of funds. The delivery and mounting phases of the lines are divided into two sections. One section for the components to be installed in J1D and the second for the components for J1T. The separation allows the installation of the components according to the accessibility of the J1T zone. The calibrations phase does not require the accessibility to the J1T zone to be closed as is the case for the WG87-QO option. It is possible to have the components of the line delivered by lines. In this case, after the delivery of the initial two lines, two additional complete lines can be delivered every three months, and then mounted.

The timing for the writing of the technical documentation is estimated from CRPP's experience with the JET-EP's Gyrotron Call for Tender and with past purchase of evacuated transmission lines for the TCV tokamak (9 lines each about 30m in length). The period for mounting and alignment of the support structures and mounting the lines is calculated from the rate at which CRPP mounted their 270m of line (time is over estimated by 50%). The delivery times are calculated for the procurement of the WG31 or WG63 waveguides, if WG45 is chosen there may be up to an additional two months required for engineering design for the new waveguide diameter.



The overall schedule could be advanced if the Call for Tender could be released before October 2002. In this case the shipment and mounting could be advanced by as much as 6 months, allowing full delivery and mounting of the lines before June of 2004. The above schedule allows for a two month delay in delivery. This could be increased to 9 months if the CFT could be sent out earlier.

10 Conclusion

The following Table is a list of the criteria which highlight the differences between the two proposed systems. The two options are judged relative to each other based off of CRPP's experience with both evacuated and non-evacuated systems plus information received from the experiences of other labs. The option which has a favorable advantage has a '+' following the comment and the option less favorable advantage with a '-'. When the two options are relatively equivalent there is an '=' sign.

WG45		WG87-QO	
=	1 Cost		=
~ 453 to 594 k\$ Price does not include supports, range of price is dependent on waveguide diameter.		>471-480 k\$ Price does not include waveguide supports nor all-metal gatevalves.	
+	2 CVD window failure		-
Lower risk. Window failure under vacuum conditions is much less likely		Higher risk. Higher risk of breakdown on window surface at atmosphere, this could lead to window failure	
+	3 Tritium leakage to J1T		-
Lower risk Leak would be confined to J1T waveguide. Gatevalves at launcher, J1T pumping Tee and J1T-J1D barrier would all close in the event of leak between torus windows.		Higher risk Higher risk. If torus window failed, tritium leak could vent directly to J1T.	
=	4 Tritium Leakage to J1D		=
Equivalent Only possible via double window failure and failure to close gatevalve at barrier. Leakage in J1T could not penetrate waveguide. Any tritium entering into J1D waveguide would be confined to waveguide, MOU and return exhaust line of pumps to J1T. No leakage to J1D.		Equivalent. Any leakage in J1T could upstream into the WG87 waveguide when shutter is not closed (this is not possible with WG45). No possible leakage into J1D (assuming waveguides are sealed). Leak would be confined to waveguide and MOU in J1D (larger volume potentially contaminated than WG45).	

+ 5 operator's opinion -	
Prefers	Accepts
= 6 Time schedule =	
From previous experience, CRPP is certain order, delivery and installation can be performed before 2005 1.8 years required for production of 18 disks from Prof. Koidl of FhG/IAF, Freiburg	Design of WG87-QO (mirror designs, supports, etc) is unique to JET. >5 years required for production of 18 disks from Prof. Koidl of FhG/IAF, Freiburg. Disks will cost more than the estimated value.
+ 7 J1T Obstructions -	
Obstruction of crane near Launcher port J1T will not be closed at any time due to ECH operation (with switching network described in Sec. 5.2)	Obstruction of passage near interferometer and south east section of J1T J1T must be closed during calibration and conditioning
= 8 J1D Obstructions =	
None	None
= 9 Remote Handling Access =	
Equivalent 10m section of line (all 8 mounted together) would be removed. Aprox. One day for removal or installation	Equivalent Mirror assemblies would be removed
+ 10 Microwave Radiation in J1T -	
~ 1.9 W / line	~ 8 to 55 kW / line
+ 11 Reliability -	
Potentially Higher Power densities in several labs prove this system is reliable	Potentially lower Power density on miter bend is high for atmospheric conditions, reliability could decrease due to breakdown
+ 12 CVD window -	
CVD disks inexpensive to replace Equivalent power densities already exceeded at JT60-U.	CVD disks expensive to replace Arcing at atmosphere on window surface could be damaging to CVD windows

+ 13 Launcher -	
Simpler (less expensive) design	more complicated (more expensive) design
+ 14 Engineering Design Work -	
Design work is an extension of WG31 and WG63, i.e. simple extension Support structure simplified version of existing CRPP supports	Detailed design to be performed (mirror design, remote alignment system, mirror precision of 0.07°, etc)
- 15 Line/launcher operation @170GHz +	
Mirrors in miter bends would have to be replaced in lines to be used at 170 GHz Higher power densities on mirrors at 170GHz	Transmission line can be compatible for the two frequencies equivalent power densities at 170GHz possible by changing last mirror in line
+ 16 ITER relevancy -	
WG45 is closer to ITER's design. WG63 would be fully compatible	Not ITER relevant
+ 17 Atmospheric absorption in J1T -	
0 W	5.5 kW / line
= 18 CVD window cavity effect =	
No precautions may have up to 1% reflection	No precautions may have up to 1% reflection
= 19 Thermal expansion in line =	
Extremely low mode conversion due to bending of lines from thermal expansion	Need bellows in line to compensate for thermal expansion, otherwise increased mode conversion
= 20 Vessel movement =	
Equivalent Last leg easily allows torus movement associated with disruption and baking	Equivalent
= 21 Transmission losses =	
WG45 10.5% WG63 9.1%	WG87-QO 9.3%
+ 22 Volume -	
Much smaller volume occupied in J1T and J1D	Much larger volume occupied in both J1T and J1D

=	22 Works	=
~1pmy and ~1tmy per year (2002-2004) for complete installation (CFT, installation, calibration, etc.)		

Some of the above criteria maybe judged differently from either the Operator's view or from the individuals who have more experience with Quasi-optical lines. Of the 22 criteria there is one case in which the WG87-QO has a clear favorable advantage, #15 (relates to operation at 170GHz, simple solutions exist for the WG45). There are 10 criteria in which the two systems are fairly equivalent. The WG45 option offers an advantage in the remaining 11 criteria. These advantages also hold for the WG63 which is the same price as the WG45 and is fully ITER relevant. The price difference of the WG63 can be between 67 and 100k\$ of the WG87-QO. There is also the hidden savings with the WG63 in that most of the items can be re-used on ITER effectively reducing the cost in half by doubling the utility.

11 Summary

The chart in the conclusion of this document demonstrates the numerous advantages of the evacuated waveguide option over the WG87-QO system for the JET-EP ECRH project. The proposal for the WG87-QO was initiated as a possible solution to the fear of pumping tritium into J1D and a potential savings in costs. The latter of these motivations has eroded away due to the availability of low cost CVD disks. The concern of pumping tritium from a leak in J1T into J1D can easily be avoided through multiple security systems and channeling the exhaust from the pumps in J1D back in to J1t. This limits maximum contamination to the volume of the waveguide, MOU, pumps and return line, a smaller volume than in the case of leakage into the WG87 waveguide. The potential tritium leakage into J1T is significantly reduced with the evacuated waveguide option (WG31, WG45 or WG63). In light of this CRPP sees no clear advantage in opting for the WG87-QO system.

This document examined the WG45 option in detail. There are two other possible waveguide diameters which could be considered, WG31 and WG63. The WG31 offers the least expensive solution (less expensive than the WG87-QO) but at the cost of increased transmission losses. The WG63 achieves the lower transmission losses for the equivalent price as the WG45 and WG63 is truly ITER relevant. However, the larger diameter is less favorable in coping with the displacements of JET during thermal expansion and disruptions, but can still accommodate for such displacement. In view of all of the above the WG45 seems to offer the optimum in flexibility for torus movements while maintaining low levels of transmission losses, should a direct relevancy to ITER not be a decisive factor.

In summary, CRPP recommends the installation of an evacuated waveguide system for the JET-EP ECRH project. Any one of the three evacuated waveguide diameters (31.75, 45 or 63.5mm) offers numerous advantages over the proposed hybrid 87mm atmospheric waveguide – Quasi-optical system at an equivalent costs. Yet, to our opinion, the later system offers no advantageous over the evacuated waveguide proposal.

12 Acknowledgements

The authors wish to thank John Doane of General Atomics for his valued assistance in preparing this document. Also, John Bird and Gordan MacMillan of the JET site are to be thanked for their assistance in determining the routing for the waveguide and Colin Flemming who acted as the interface between the authors and the JET team. Bernhard Piosczyk from FZK offered valuable information in regards to the pricing of the CVD disks and technical information on the housing unit.

This work was partly supported by the Swiss national Science Foundation.