LRP 735/02 December 2002

General description of the evacuated wave guide transmission line for the JET-EP ECRH project

M.A. Henderson, S. Alberti, J. Bird, J. Doane,
B. Elzendoorn, C. Flemming, T.P. Goodman,
F. Hoekzema, J.-P. Hogge, G. MacMillan,
J.–C. Magnin, B. Pioscyk, L. Porte, M.Q. Tran,
A.G.A. Verhoeven

Submitted to the JET archives: EP-ECH-TLR-R-002

ISSN 0458-5895

GENERAL DESCRIPTION THE EVACUATED WAVE GUIDE TRANSMISSION LINE FOR THE JET-EP ECRH PROJECT

M.A. Henderson[1], S. Alberti[1], J. Bird[2], J. Doane[3], B. Elzendoorn[4], C. Flemming[2], T.P. Goodman[1], F. Hoekzema[5], J.P. Hogge[1], G. MacMillan[2], J.C. Magnin[1], B. Pioscyk[6], L. Porte[1], M.Q. Tran[1], A.G.A. Verhoeven[4]

[1] Centre de Recherches en Physique des Plasmas,
Association EURATOM - Confédération Suisse
Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland

[2] EURATOM-JET UKAEA Culham
[3] General Atomics- San Diego, CA, USA
[4] EURATOM-FOM-Instituut voor Plasmafysica 'Rijnhuizen'
[6] EURATOM-FZJ-Julich
[6] EURATOM-FZK-Karlsruhe

The goal of this document is to provide a detailed description of the preliminary design and technical information of the proposed 63.5mm diameter, corrugated HE_{11} evacuated transmission lines for JET-EP ECRH system[1,2]. The JET-EP-ECRH system envisions six to eight 1.0MW gyrotrons at 113.3GHz. The microwave power from a gyrotron is to be transmitted to the launcher of the tokamak via a transmission line. On average each line is 72m in length and includes 9 miter bends, two switches, a calorimetric load, pumpout tees, gate valves and DC breaks. The material contained within this document represents the design status as it stood upon the cancellation of the project in the February, 2002. The initial phase planned for the installation of six ECH units (power supply + gyrotron + transmission line + launcher) with the capability of an additional two units at 170GHz. The design was made for a total of eight lines, even though only six lines may be discussed in this document. A more compact version of this document is planned for submission to Nuclear Fusion and is available in the CRPP archieves [3].

Submitted to the JET archieves :EP-ECH-TLR-R-002

1. SCOPE

The goal of this document is to provide a detailed description of the preliminary design and technical information of the proposed 63.5mm diameter, corrugated HE_{11} evacuated transmission lines for JET-EP ECRH system[1,2]. The JET-EP-ECRH system envisions six to eight 1.0MW gyrotrons at 113.3GHz. The microwave power from a gyrotron is to be transmitted to the launcher of the tokamak via a transmission line. On average each line is 72m in length and includes 9 miter bends, two switches, a calorimetric load, pumpout tees, gate valves and DC breaks. The material contained within this document represents the design status as it stood upon the cancellation of the project in the February, 2002. The initial phase planned for the installation of six ECH units (power supply – gyrotron – transmission line – launcher) with the capability of an additional two units at 170GHz. The design was made for a total of eight lines, even though only six lines may be discussed in this document. A more compact version of this document is planned for submission to Nuclear Fusion and is available in the CRPP archieves [3].

After a brief introduction of the historical choice for this system in chapter 3, the criteria for optimizing the design of this system will be presented in Chapter 4. Chapter 5 provides a general overview of the whole system and chapter 6 a description of the wave-guide elements. The expected transmission efficiencies are discussed in Chapter 7 followed by a brief description of miscellaneous items in chapter 8 and then a conclusion in Chapter 9.

2 REFERENCE DOCUMENTATION

[1] A.G.A. Verhoeven et al, 12th Joint Workshop on ECE and ECRH, May 13-16, 2002, to be published.

[2] J. Pamela, Fusion Engineering and Design 56-57 (2001) pp. 19-28.

[3] M.A. Henderson et al, LRP 736/02: Design of the evacuated wave guide transmission lines for JET-EP.

[4] A.G.A Verhoeven, et al, Proc. of the Display and Vacuum Electronics, May 2-3, 2001, Garmisch-Partenkirchen p.345.

[5] A. Fernandez, et al, Transmission line design options and costing, JET-EP ECRH Desgin Review Meeting, March 12-13, 2001 Culham.

[6] F. Hoekzema, Meeting of the CC-ECW, Geneva July 3-4,2001.

[7] A. Fernandez, Meeting of the CC-ECW, Geneva July 3-4,2001.

[8] J.A. Hoekzema, et al, JET-ECH-TLR-T-002: Preliminary design report for QO transmission line.

[9] M. Henderson, et al, LRP 719/02: General Description of the Evacuated Wave-guide Transmission Line for the JET-EP ECRH Project

[10] A.S. Kaye, JET EP-ECH-GEN-T-002: Operator Requirements for the ECRH Transmission Lines.

[11] B. Piosczyk JET-ECH-TLR-WIN-R-001: 2001 FZK final order report.

[12] B. Elzendoorn et al, 2002 Proc. of the 22nd Symposium on Fusion Technology, Helsinki, to be published.

[13] W. Kasparek et. al., Frequenz, 9-10 (2001) Vol. 55, pp. 263-269.

[14] J.L. Doane and C.P. Moeller, Int. J. Electronics 77 (1994) pp. 489-509.

[15] J.L. Doane GA internal report: Some design considerations for high-power corrugated wave guide transmission lines.

3 INTRODUCTION

3.1 Historical overview

Originally the transmission system for the JET-EP ECRH project had been an evacuated 63.5mm diameter corrugated wave-guide[2]. However, the design went through several alterations motivated by cost savings or potentially reduced risks of Tritium leakage from J1T (torus hall) to J1D (diagnostics hall where the gyrotrons will be located). From a cost perspective, evacuated wave-guide has been traditionally viewed as an expensive method of transmitting the microwave power from the gyrotrons to a tokamak. A typical 72m wave-guide (without CVD window nor launching antenna) is estimated to cost ~450k€ (January, 2001 prices), over an equivalent distance a quasi-optical (QO) mirror system was investigated which offered a transmission system per line at ~325k€, a 23% reduction in cost[4]. Furthermore, the Operator expressed concern with an evacuated wave-guide line[5], which traversed the barrier between J1T and J1D. If a Tritium leak occurred in J1T and the Tritium could enter into the wave-guide via leaks in the wave-guide, or if the CVD window on the torus failed, Tritium could leak directly into the wave-guide. Once Tritium enters the wave-guide the some of the Tritium would reach the pumps near the gyrotron and be expelled into J1D thus increasing the contaminated zone. Using a QO line with a CVD window at the barrier between J1D and J1T there would be a low risk of Tritium contamination into J1D.

A complete QO line from Gyrotron to torus had drawbacks as well; the section of the line in J1D would require shielding to avoid stray radiation from damaging equipment and for personnel safety. The overall size of the QO line enclosure would occupy a significant volume of J1D and obstruct the use of an overhead crane. All envisioned routings were deemed unacceptable to the Operator, which led the design team to propose a hybrid design of an atmospheric 87mm wave-guide line in J1D and a QO line in J1T. The atmospheric line prevented the pumping of Tritium from J1T to J1D and also avoided radiation leakage and minimized the occupied volume in J1D. The overall costs of the hybrid wave-guide/quasi-optical line (WG87-QO) maintained the same cost per line as a full Quasi-optical system[6,7].

The above costs for the different transmission systems included all elements from the output of the Matching Optics Unit (MOU) at the gyrotron up to but not including the CVD diamond window-housing unit. This last element can vary in cost depending upon the diameter and thickness of the CVD disks used. Recently, CVD disks have become available through FhG/IAF, Freiburg that offers a significant reduction in the price. Despite this reduction, the price of a housing unit for the WG87-QO line would cost ~180k€ bringing the total cost per line to ~545k€. The CVD unit for the WG63 line would cost ~110k€, the WG63 uses a smaller diameter disk than the WG87-QO. The total cost of the WG63 line including the CVD housing unit would then be 560k€, basically equivalent to the WG87-QO proposal. The traditional view of the evacuated wave-guide lines as being expensive had been misleading, an evacuated wave-guide line is equivalent in cost to a Quasi-Optical system (prices based on international conversion rates of November 2001). As a result of this comparison the JET-EP ECRH team re-evaluated the two proposals anew and considering the advantages and dis-advantages of each in relation to the JET device[8,9].

The conclusion of the comparison re-adopted the WG63 proposal in part for its small volume in both J1T and J1D and also a reconsideration of the wave-guide Tritium barriers. The new design would channel the exhaust from the turbo pumps back to J1T thus limiting the Tritium exposure to the wave-guide lines, MOU, turbo pumps, and return line, a volume equivalent to the WG87 line in J1D. A further advantage to the WG63 line is that it is ITER relevant and the wave-guide components could be built broadband to facilitate both the 113.3 GHz for JET and 170GHz for ITER. Reusing the wave-guide elements on ITER reduces the effective cost of the wave-guides lines in half to ~280k€. Thus the design of the WG63 line for JET has been performed in light of reusing the maximum number of components for the ITER device and designing the system to be as ITER relevant as possible[3].

3.2 General Description

This section is devoted to providing a brief description of the transmission line and the JET installation relevant to the ECRH system without covering too much of the design detail. There will be 6 gyrotrons located on the south side of the J1D building. Each gyrotron will be connected to a wave-guide line, which transmits the microwaves to the entry port of the launching antenna at the torus in J1T. An overall view of the two buildings and the location of the different elements are shown in Figure 1. Each wave-guide line leaves the MOU horizontally and travels to the east end of the platform. The first miter bend in each line (MB #1) directs the wave-guide downward to a level of >2.5m above the ground floor and then MB #2 directs the line toward the J1T building. After passing through the barrier between J1T and J1D, the wave-guide lines are redirected by MB #3 upward at an angle to a height >7.2m above the J1T floor. The wave-guide lines follow a 'dogleg' (MB's #4-6) around the ventilation shaft in the southeast corner of J1T and then along the east wall opposite of the port in Octant 1. MB #7 sends the wave-guide toward the torus a second 'dogleg' (MB's #8-9) deviates the wave-guide around the KN3 diagnostic and into the launching antenna's port. A view of the wave-guide lines in J1T is shown in Figure 2.

Each line is comprised of the following elements: DC break on both the gyrotron and torus ends, 9 miter bends, a switching network to direct the beam either to the torus or to a calorimetric load, in-line wave-guide bellows for compensation of the thermal expansion (where necessary), two gate valves for vacuum and Tritium barriers, a pumpout Tee for evacuating the wave-guide, a power monitor miter bend and a window housing unit. These items are explained individual in more detailed in chapter 6. Overall the average line length is 72m and an average transmission efficiency of ~90%.

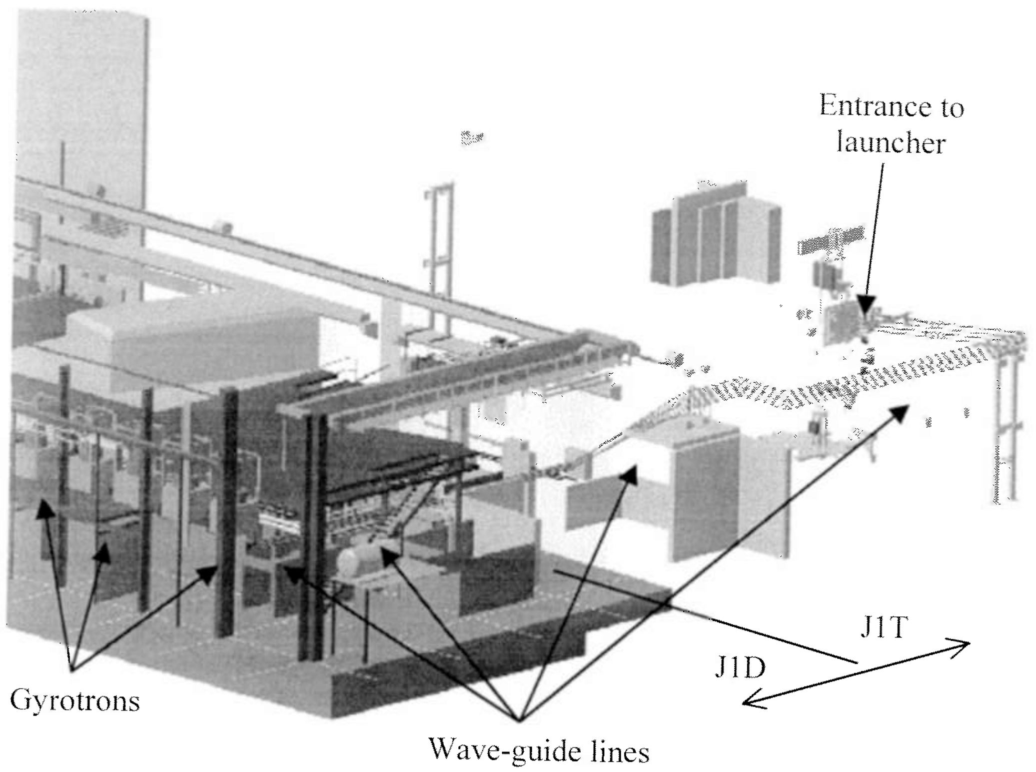


Figure 1 View of the entire wave guide line from the gyrotrons up to the entrance to the JET torus.

4 DESIGN CRITERIA

Several criteria were used in the design of the WG63 wave-guide line, but in principle the goal was to minimize losses in the line while designing a system that is ITER relevant, facilitate the operation of the gyrotrons and satisfies the requirements of the JET tokamak[10]. The principle criteria can be grouped into the following categories:

- Satisfy the security rules of JET-EP [10]
- Accommodate JET torus displacement (thermal cycles and disruption events)
- Accommodate gyrotron conditioning and calibration
- Minimize obstructions in J1T and J1D
- Optimization of transmission efficiency
- Compatibility with ITER

The goal of this section is to describe each of the above criteria and explain how the proposed WG63 satisfies each requirement.

4.1 Personnel Safety

There are a few risks to personnel safety in the transmission of high power microwaves from the gyrotron to the JET torus, which include:

- Window failure resulting in Tritium leakage to J1T or J1D
- Neutron radiation into J1D
- Microwave leakage from wave-guide line
- Electrical shock
- Injury arising from contact with line (or bumping one's head)

4.1.1 Tritium Leakage

There are two Tritium barriers for the JET site, the torus chamber and the barrier between J1T and J1D. Since the wave-guide line pass though both of these barriers, the line itself could allow for Tritium to leak out of the torus and into either J1T or J1D. The wave-guide line maintains JET's two-barrier philosophy, see figure 3. The first barrier is at the exit of the wave-guide in to the launching antenna. This barrier consists of an all-metal gate valve and a double disk CVD window (on the gyrotron side of the gate valve). The inner space between the two disks is monitored; a disk failure would change

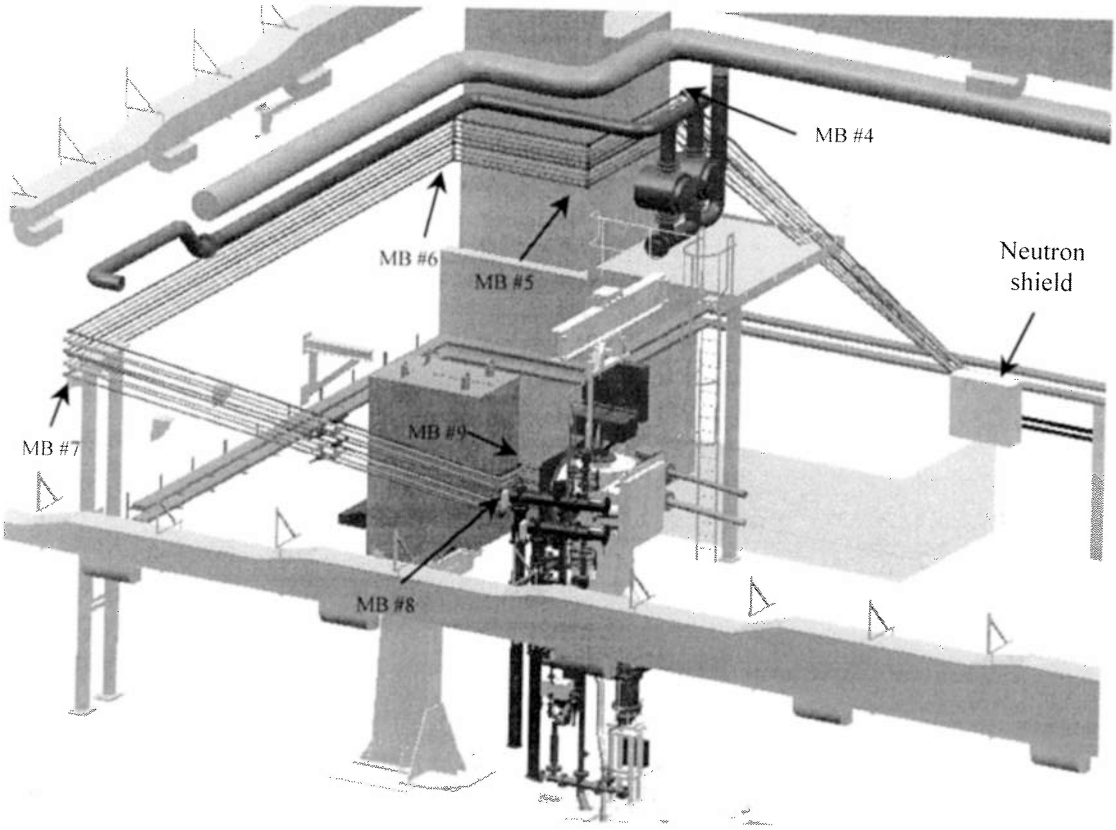


Figure 2 View of the wave guide lines in J1T leading up to the entrance to the launching antenna-pumping port assembly.

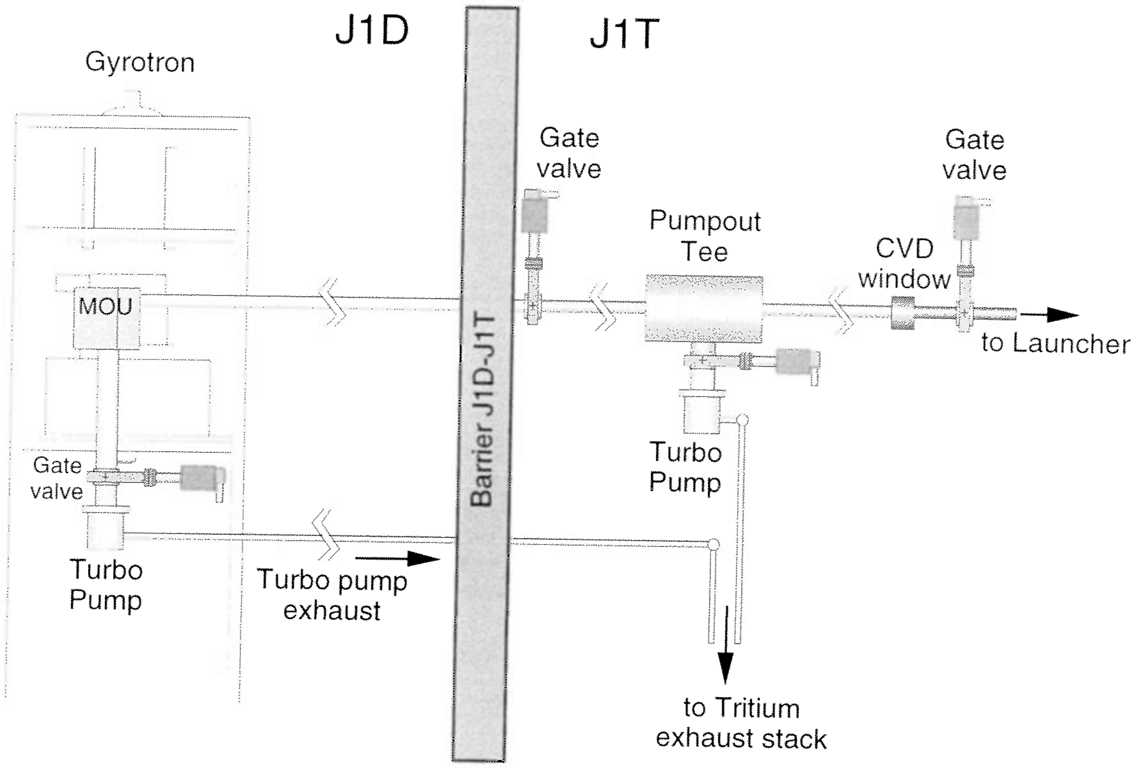


Figure 3 Schematic of the Tritium barriers to be used on the ECH transmission lines.

this pressure and send a command to close the gate valve at the torus. A second gate valve is placed on the J1T side of the barrier wall between J1T and J1D. This gate valve would also close in the event of a change in pressure in the inter-vacuum region between the two disks.

An additional third barrier is added to the WG63 design to insure no leakage of tritium in to the wave-guide could penetrate into the J1D zone. In the case of tritium leakage through the double disk window and a failure to close all gate valves, the Tritium could inter into the J1D zone via the wave-guide and travel all the way to the MOU and attached turbo pump. A third gate valve between the MOU and turbo would also be interlocked on the inner vacuum pressure between the two disks. Any Tritium leakage past this third gate valve would enter into the pump and pass out its exhaust which would be then directed back to the exhaust stack in the J1T zone (not to J1D, thus limiting the maximum contaminated space to the volume of the wave-guide, MOU, pumps and exhaust line.

4.1.2 Neutron Radiation into J1D

The barrier between J1T and J1D will be drilled to allow passage of the 6 wave-guide lines. The holes will be about 100mm in diameter (external diameter of the wave-guide is < 80mm) to insure ample space for precision alignment of the wave-guide through the hole. Once the wave-guides are mounted the remaining space will be filled with

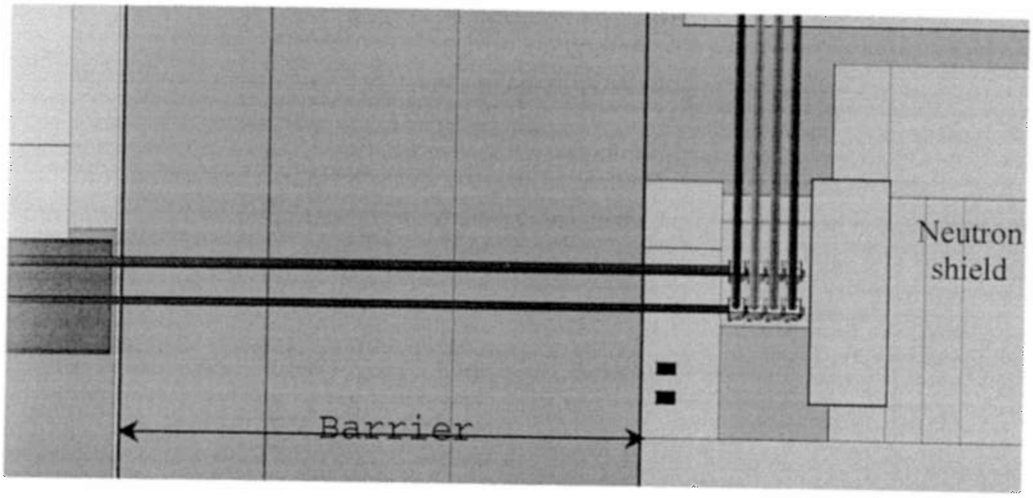


Figure 4 View of the wave guide passing through the barrier between J1D and J1T. A 50cm concrete block is added on the J1T side to reduce the neutron flux passing through the wave guide in to JD.

polyurethane beads and both ends of the passage through the barrier will be capped to insure minimum airflow.

Calculations of the neutron flux through holes with a 300mm diameter were performed for the WG87-QO design. To insure low levels of neutron flux in J1D (<1millSievert/year), a 50cm block of concrete on the J1T side would be added to attenuates the neutron flux from J1T to J1D. The WG63 design will maintain the extra concrete shielding which is positioned as shown in Figure 4.

4.1.3 Microwave Leakage

The majority of components in the wave-guide line are solid wall T-6062 Aluminum alloy, which does not permit passage of millimeter wave radiation, the wave-guide wall is over four orders of magnitude greater than the skin depth of aluminum. However, there are some components made of either ceramic or epoxy (e.g. in-line DC break and ceramic DC breaks in pumping stations), which permit some transmission of the microwaves out of the wave-guide. The leak rates are below the safety requirements, for example, the in-line DC breaks are rated at $\leq 5mW/cm^2$ at a distance of 50cm from the DC break for 1.0MW in the line. This level can be further reduced with the addition of a microwave absorber (non-conducting) around the DC break. The ceramic DC breaks in the pumping stations (both on the pumpout tees in J1T and on the MOU pumping station) will have a metal grill placed before the ceramic piece. The grill will reflect any stray microwave radiation, avoiding any power from arriving at the ceramic piece. Thus the whole transmission line will allow the safe passage of personnel near all elements without risk of microwave irradiation.

4.1.4 Electrical Shock

Each wave-guide line will be isolated from both the connected gyrotron and from the torus via an in-line DC Break with ≥5kV isolation. Aside from the DC break, all components are of either Aluminum Alloy or Stainless Steel with all-metal Helicoflex™ seals between each component providing a sufficient electrical connection throughout the line's length. Each line will be connected to building ground, which will insure no risk of electrical shock at any time when personnel come near the wave-guide line.

4.1.5 Injury arising from Physical contact

Aside from the gyrotron platform, the wave-guide lines will be mounted above head level (>2.5m from the floor) and supported by hanging supports or supports from the wall. This avoids all obstructions on the ground floor and minimizes the risk of head or body injuries from low hanging elements.

4.2 Transmission optimization

The total hardware costs for the JET-EP ECRH project is estimated at ~20M€ for the generation of ~6.0MW from 6 gyrotrons. This costs corresponds to more than 3.3€ per generated Watt. All of the various systems studied for the JET-EP ECRH project had transmission losses of the order of 10%, or 100kW which corresponds to a relative cost of ~330k€ per 1.0MW ECH system (power supply - gyrotron - transmission line - launcher). The costs associated with the lost power are the same order of magnitude as the cost of a given transmission line (~450k€ not including CVD window unit). Therefore, in the design of this transmission line system, care is taken to minimize the number of elements which are lossy (i.e. miter bends and items with high mode conversion). This section discusses briefly how the line was designed in order to minimize the transmission losses.

4.2.1 Minimize quantity of miter bends

The wave-guide element with the highest losses is the miter bend. Each WG63 bend has ~0.63% (0.2% worse case ohmic absorption and 0.43% in mode conversion) associated losses which corresponds to a cost of 44.1k€ per bend. The purchase price of each miter bend is ~1/5th of this cost, therefore it is of great interest to minimize the number of bends purely from a perspective of the cost of each Watt lost due to ohmic attenuation and mode conversion, as is described in Section 5.3.1.

Since the transmission line is to be installed in an existing laboratory, the installation of the lines may require modifications to existing structures or the line could be deviated around a given obstruction at the additional cost of wave-guide items and additional losses. The above cost of about 54k/bend (including the hidden cost of the lost power) provides a figure of merit to compare with the cost of modifying a given structure. The best example of this is in the southeast corner of J1T. Two additional miter bends per line are needed to deviate the line around the ventilation shaft at a cost of more than 0.6M€ (six lines), rather than passing between the shaft and the wall. The cost of modifying the ventilation shaft could be much cheaper than 0.6M€, thus reducing the overall costs and simplifying the wave-guide line. A cost estimate of modifying the shaft would have been performed if the project had continued.

4.2.2 Minimize losses due to wave-guide sagging and support misalignment

A given length of wave-guide will sag in between two successive supports. The bending will cause a certain amount of power coupled to other modes, with the coupled power increasing with the depth of the sag. This would imply that to decrease losses due to mode conversion, the number of supports should be increased until the wave-guide is as straight as possible, however, the wave-guide is slightly bent between any two supports due to the imprecision of aligning the two supports. Over short distances (<10m) the precision in aligning the supports is independent of the distance between supports, typically ±0.5mm. At very short spacings between the supports, the wave-guide will bend to match the support misalignment. There is some optimum support spacing for a given wave-guide diameter and operating frequency to minimize the mode conversion between high losses due to misalignments (short support spacing) and high losses due to wave-guide sagging with long support spacings. Figure 5 is an example of a standard alignment error of ±1mm while varying the support spacings for 72m of a wave-guide line. The optimum spacing seems to be between 4 and 6m while avoiding spacings at 5m (corresponding to a beat wavelength between fundamental and higher order modes).

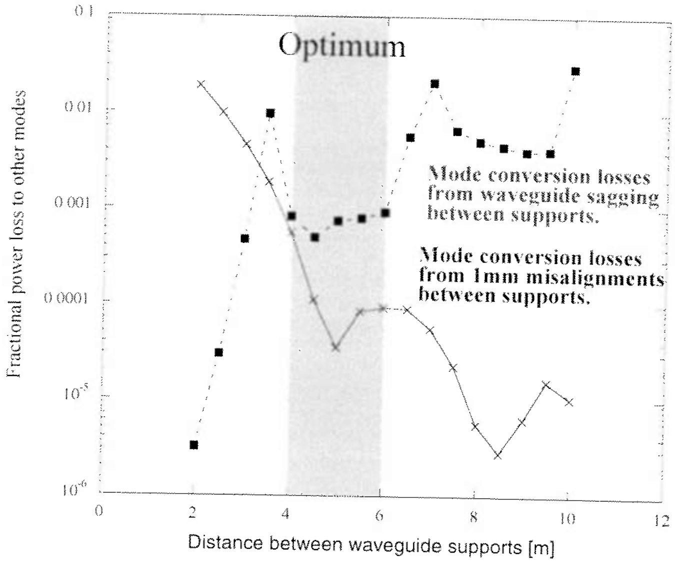


Figure 5 Combination of the losses associated with misalignment between two supports and the losses associated with the waveguide sagging due to gravity. A minimum in the mode converted seems to occur with support spacings between 4 to 6m.

Further studies would have been performed to choose variable support spacings based on available support locations in J1D and J1T. There are only a finite number of scenarios for supporting the wave-guide lines (based on existing pillars, miter bend locations, etc.). For each given scenario a random misalignment can be introduced at each support to give an estimate of the potential mode conversion for that particular scenario. Several cases of random error would have been introduced to approximate the type of losses, which could be expected for any given scenario. The optimized location of the support structures corresponds to the scenario that has the lowest coupled power due to sagging and misalignment).

4.3 ITER relevancy

Designing a completely ITER relevant transmission line on JET-EP is not possible to perform since the operating frequency and power of the two systems are not the same. For example: since the European community plans to provide a 2MW tube for ITER the JET-EP line should maintain similar power densities. This implies JET-EP should use a ~45mm wave-guide diameter for the 1MW tubes. Yet scaling based on the wavelength of 170GHz implies an ITER relevant waveguide diameter at 113GHz would be 95mm diameter waveguide to simulate equivalent losses in bending and alignment of the waveguide. So in adopting the JET-EP transmission line to be ITER relevant, certain criteria were judged more critical for ITER than others.

Also, some design criteria, which normally would be considered optimal for JET, were changed to be ITER compatible. The choice in wave-guide diameter is a prime example. Initial studies led the design team to consider 45mm wave-guide as the optimum size for JET[9]. This size offered a balance between the low mode coupling of small diameters due to bending (for compensation of torus displacements) and the low losses in miter bends in large diameters. Despite these conclusions the 63.5mm diameter was chosen for financial reasons. The wave-guide is inherently broadband, so that the wave-guide elements could transmit both JET and ITER ECH frequencies. Plus the wave-guide lines installed on JET would supply all of the wave-guide needed for the 4 lines for the EU 2MW gyrotrons. Re-use of the elements offers a significant reduction in the hardware costs associated with the ECH system for the two machines

The ITER relevant items that have been addressed in this design include the following items:

- Testing of the alignment techniques
- Modeling of losses to converted modes from bends and misalignments
- Testing of the CVD window housing unit
- Testing of the operation functionality of the system
- Testing of the Tritium security systems

These topics influenced the design of the transmission line as described in the relevant sections of this document.

4.4 Costs

The motivating factor in reviewing the several transmission systems as mentioned in the Introduction was driven with the intent to reduce the total costs of the transmission system. Despite the fact that the transmission line (between MOU and Launching Antenna) represents only a small percentage of the total hardware costs (~15%), a considerable amount of time and effort was invested to minimize the related costs. The main criteria for reducing the costs included:

- Smaller wave-guide diameter tended to be cheaper
- The CVD disks represent a significant cost of the transmission line.

- Chose systems which are already commercially available, no investment in engineering & design
- Re use of any component on another fusion device effectively reduces the cost of these components in half.

The later of these criteria dominated the overall price of the system and justifies the choice of the 63.5mm wave-guide.

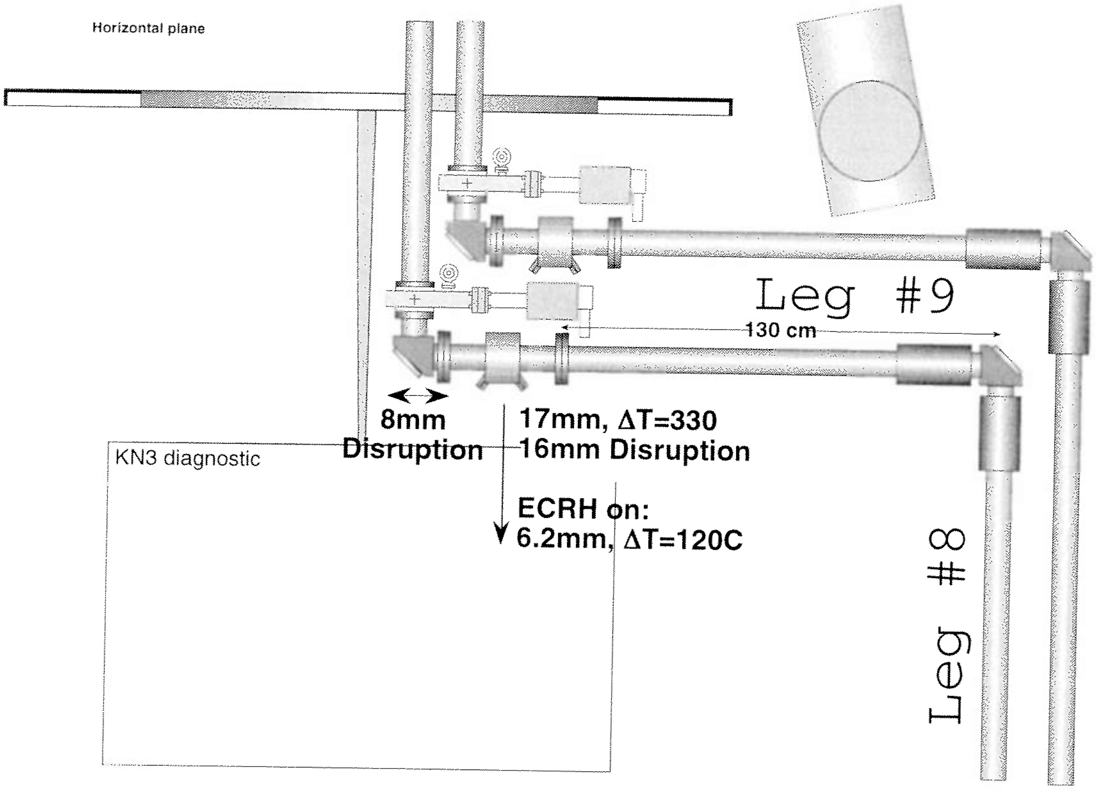


Figure 6 The last leg of the waveguide line will bend to compensate for the torus displacements associated with baking and plasma disruptions.

4.5 Torus Displacements

The JET torus undergoes a large displacement during disruptions and thermal baking cycles. The wave-guide can move up to 16mm radially and 8mm toroidally during disruptions and 17mm radially during thermal cycles torus baking). The wave-guide sections near the torus are designed to bend in adjusting to these displacements, see figure 6. Due to the large magnitude of the displacements the more flexible smaller diameter wave-guide (45mm) is preferable. Yet if the last sections of the wave-guide before the launcher are lengthened, the internal stresses of the wave-guide are reduced to well below the Yield strength for the 63.5mm diameter. Wave-guide sections of ~1.5m in length are sufficiently long to compensate for all of the torus displacements[3].

4.6 Gyrotron conditioning/calibration

The operation and calibration of the gyrotrons places certain design requirements on the transmission line, for example the lines need the flexibility to direct the beam either into the torus or into an evacuated load on a day-to-day basis. At the start of each operating day the gyrotron is fired into a load at short or moderate pulse lengths (from a few milliseconds to about two tenths of a second) to check the operating beam current of the tube. Also after long periods (several months) of non-operation the gyrotrons may need re-conditioning. The re-conditioning requires operating the gyrotron at long pulse lengths (>1s) for several pulses. Both of these requirements force the use of an evacuated switch that re-directs the beam either to the load or to the Tokamak.

Each gyrotron-transmission line combination will need to undergo a calibration procedure. The delivered power to the launching antenna is measured and cross-calibrated to the power monitor power signal depending on the beam current in the tube, magnetic field and cathode voltage. The delivered power to the torus can only be measured after the beam has been propagated down the whole length of the wave-guide. A double in-line switch has been introduced to allow both conditioning of the gyrotron and calibration of the entire line to be performed without hindering tokamak operation nor requires human intervention into the torus zone. This feature is described in detail in section 5.4.3.

4.7 Minimization of obstructions

The design of the transmission lines was made to avoid as many obstructions as possible. One of the advantages of the evacuated wave-guide is that it is capable of transmitting a large power levels in a small volume and at low losses. Several possible routings were studied which fall into three classifications:

- Passage through the basement
- High passage in J1D then along the wall in J1T
- Low passage in J1D then along the wall in J1T

The routing that minimized the obstructions to personnel, equipment and the overhead crane, while maintaining the minimum number of miter bends (<10) was considered. Passage through the basement offered the minimum obstruction to personnel and overhead crane yet required several existing elements to be displaced and increased the number of miter bends to above 10. A high passage in J1T blocked completely the use of the overhead crane. Two low passage routes in J1D (between 2.5 and 3m from the floor) were found which offered essentially no obstructions. The passage in J1T tried to keep the wave-guide close to the wall (avoiding obstructions to the overhead crane) and high on the wall (avoid personnel passageways), see figure 7.

Of the two low passages in J1D, one option arrived into J1T in a region far removed from personnel pathways (avoiding the narrow passageway between the south wall of

J1T and the interferometer). This route, depicted in figure 2, was preferable since the added neutron shielding would constrict the passageway around the interferometer.

5 GENERAL OVERVIEW

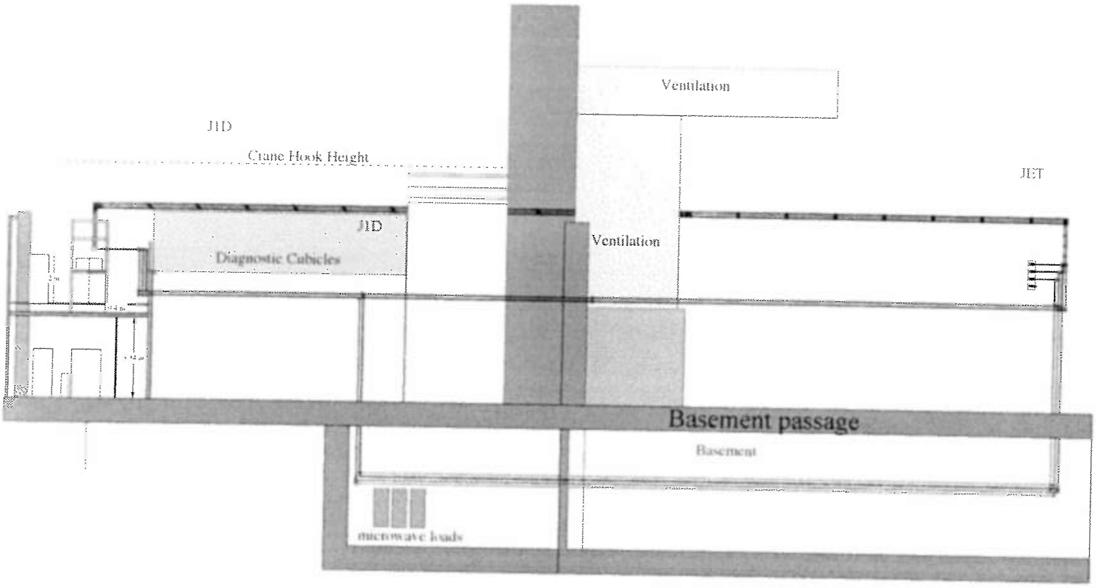


Figure 7 View of the three ranges of waveguide routes investigated for the transmission line: high passage (which obstructed the overhead crane passage), basement passage (which had too many miter bends, >10) and low passage (optimum routing).

The overall transmission line can be divided into different regions along its path from the gyrotron to the launching antenna at the torus. In principle there are four main regions:

- J1D zone
- Barrier between J1D and J1T
- J1T zone
- Line-launcher interface

The goal of this section is to describe each of these regions in detail starting from the gyrotron.

5.1 J1D zone

The wave-guide region in the J1D zone is divided up into two sections, gyrotron platform and ground floor passage. The gyrotron platform, installed on the southern side of the J1D building, will support the gyrotrons, calorimetric loads, control racks and space for a local operating control unit. The ground floor passage includes the region of the wave-guide from the platform to the barrier between J1D and J1T. The wave-guide in the passage region will be supported from the steel structure of the diagnostic platform and will have no obstructions below 2.5m above the ground floor. Only 6 gyrotrons and associated wave-guide lines are shown in figure 8.

5.1.1 Gyrotron platform

The 113.3GHz gyrotron has a horizontal output from the MOU, see figure 8. The gyrotrons are numbered in order from east to west. In order to compact the wave-guide lines gyrotrons #3 and #5 will be mounted about 30cm higher than the other gyrotrons. This allows the lines leaving from these gyrotrons to pass above the MOU and wave-guides of #2 and #4 respectively. The wave-guides leaving each of the MOUs are directed to the east (or to the west for gyrotron #1) toward the north-south plane of passage into J1T. In this plane the lines are grouped together and descend to a height of ~2.0m above the ground floor and then turn toward J1T, see figure 9.

Each wave-guide line on the platform will include a DC break just after the MOU (this element provides electrical isolation between the gyrotron and the line), straight wave-guide section, vacuum compatible switch (allows directing beam to the torus or to a calorimetric load) – load assembly, and a miter bend (directs the beam down to the ground floor level). There will be one calorimetric load shared between two gyrotrons. A switching network (see schematic shown figure 14) allows the connection of either two neighboring gyrotrons on to the load. The reduction of one load (with the addition of the switch and wave-guide pieces) reduces the overall costs of the average transmission line by ~10%.

Support structures of the wave-guide will be installed at the MB #1 and along the long sections of wave-guide between the miter bend and the MOU output. These support structures have not been fully designed but will be equivalent to the structures, which will be used for supporting either the miter bends or the wave-guide in the other sections

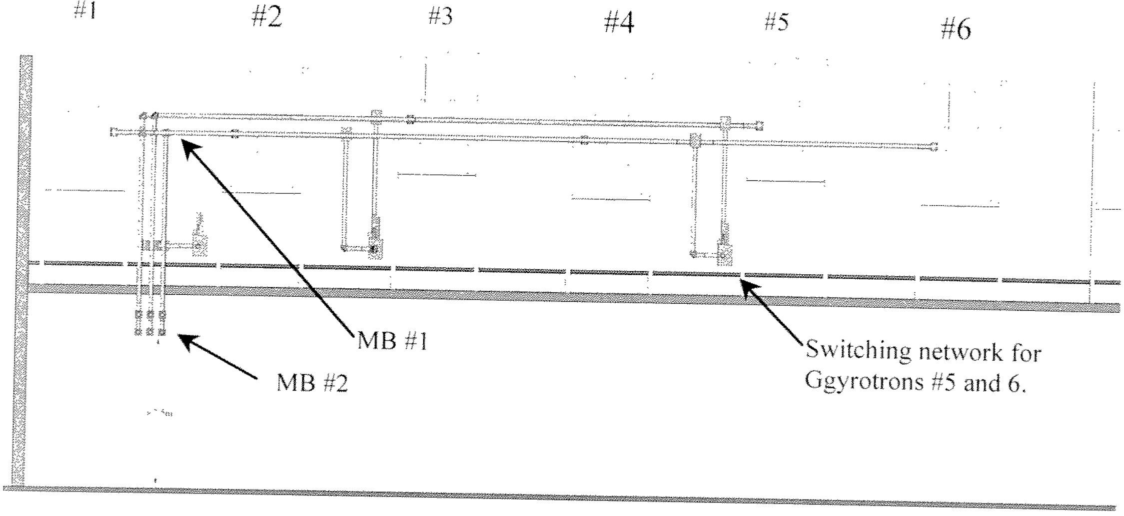


Figure 8 View of the gyrotron platform and wave guides from the north. The MOU output is horizontal. The calorimetric loads (not shown) are to be connected to the swtiching unit at the base of every other gyrotron.

of the line. These supports will be described in more detail in the chapter 8.

The wave-guide line is directed downward with the first miter bend (MB #1) in each line and passes through the floor of the platform, see figure 9. The design of the platform will need to insure that the structure will permit the passage of all the wave-guide lines.

5.1.2 Ground floor passage

A second miter bend (MB #2) directs the wave-guide toward the J1T building as shown in figure 9. This section of line consists principle of straight wave-guide sections and

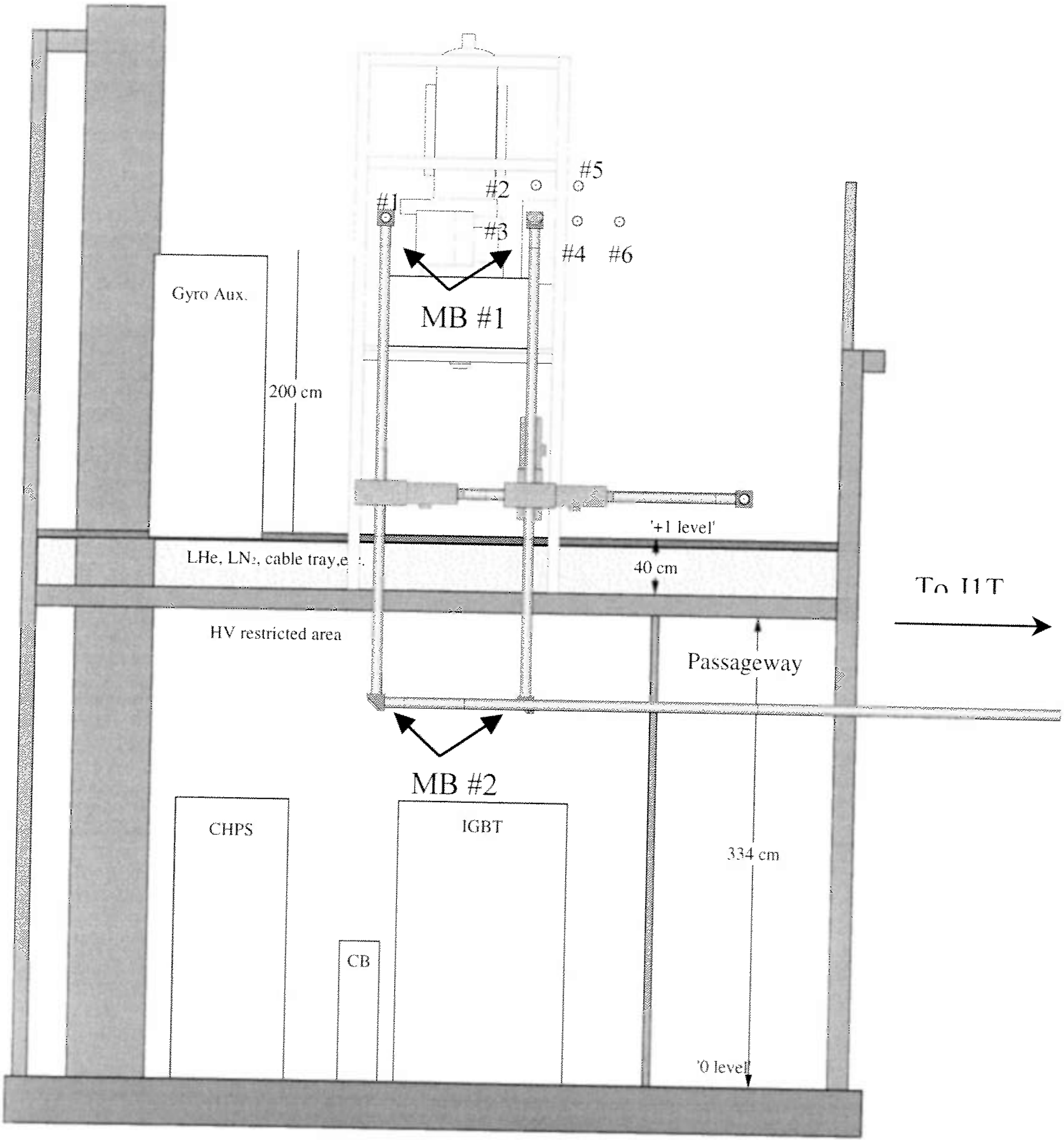


Figure 9 Layout of the gyrotrons and wave guide lines on the gyrotron platform as viewed from the East. The horizontal section of waveguide runs toward the J1T building and is positioned >2.5m above the ground floor.

one in-line wave-guide bellows. The bellows compensate for thermal expansion and contraction during operation and due to variations in room temperature (±15°). The average length of each section is about 19m before leading up to the passage through the barrier.

The wave-guide lines are mounted in a 2 by 4 grid (2 rows of four wave-guide lines). The horizontal spacing between each line is 150mm and the vertical spacing is 300mm. There will be a minimum of >2.5m of clearance between the floor and the lowest part of the wave-guide lines.

The wave-guide will be supported from the steel structure of the diagnostic platform. The support has not been designed, yet is planned to be as simple as possible and allow precision alignment of the wave-guide lines to within a ±0.5mm. Each wave-guide is supported from a cradle mounted on a cross bar. The cross bar can be adjusted vertically and each cradle can be displaced horizontally. CRPP will be responsible for the construction of the support pieces. The Operator would provide a mounting plate that allows the supports to be attached to the existing steel structures.

5.2 Barrier

The wave-guide lines have to pass through the barrier between J1D and J1T. The barrier is a 3.8m thick concrete wall that provides shielding from neutrons and x-rays as well as prevents Tritium leakage into J1D. The passage of the line should try to maintain the integrity of this barrier for both the neutrons and passage of gaseous particles. The components in this section of the wave-guide line consist of a special 4.26m section of wave-guide (two 2.13m wave-guide assembled together), an all-metal wave-guide, MB #3, neutron shield (provided by the Operator), and a support structure placed inside of the barrier wall (provided by CRPP).

A rectangular hole of about 500mm (vertical) by 650mm (horizontal) will be cut out of the barrier wall. A steel structure with tubes (ϕ_{in}=100mm) will be inserted in the hole and the regions outside of the tubes will be refilled with concrete. The tubes will be rigidly held in place to prevent them from floating upward when the concrete is installed. The larger bore diameter tubes provide some clearance between the wave-guide and the tube plus some flexibility in the final alignment of the lines. Once the wave-guides are installed the region between the wave-guides and the tubes will be filled with polyurethane beads and then each end capped to prevent leakage of gas particles from J1T to J1D.

An all-metal gate valve will be placed on the J1T side of the barrier. This gate valve provides a second level of security between J1D and the CVD diamond windows near the torus in case of window failure. (Note: first level of security is the all-metal gate valve between the launcher and the CVD windows). The gate valves will be mounted as close to the barrier wall as possible. The third miter bend in the line will be just after the gate valves.

The neutron shield is not addressed in this report; it is under the responsibility of the Operator. This additional shield, as was shown in figure 4, will be located close to the wall and will not obstruct personnel passageways.

5.3 J1T Zone

The wave-guide passes into the J1T zone near the south-east corner at a height of >2.5m and then bends upward to a height 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 personnel up until the point where the wave-guides leave the wall and descend toward the launcher port (see figure 2). This last section of wave-guide breaching the east wall to the launcher port will obstruct the passage of the crane. No obstruction of personnel passageways will exist within the J1T (and likewise J1D) zone.

The wave-guide in J1T can be divided up into four sub-sections:

- South wall of J1T
- East wall of J1T
- Trestle bridge, section breaching east wall to launcher port
- Wave-guide near launcher

5.3.1 South wall of J1T

This section of the wave-guide leaves MB #3 and inclines upward to the ventilation shaft and the platform to the west of the shaft. The components included in this section are straight wave-guide, an in-line pumpout Tee and a set of three miter bends (MB's #4, #5, and #6) to dogleg the wave-guide around the ventilation shaft. A second possible routing has been investigated which would pass the wave-guide behind the ventilation shaft. This would require dismantling the shaft during the installation of the wave-guide, but would decrease the number of miter bends in each line by two and decrease the losses associated with the miter bend. If the shaft could be modified for less than ~650k€ (equivalent price of 2 miter bends per 6 lines at 54k€/bend including additional cost associated with microwave losses), then the second routing (requiring the modification of the ventilation shaft) should be chosen. Due to the canceling of the project, this and other decisions were not brought to full maturity. Only the initial routing with a total of 9 miter bends will be presented in this document.

The pumpout Tee allows the pumping of the wave-guide via a gap. Connected to the pumpout Tee will be a dry-vac pump that has the turbo pump and roughing pump (plus the associated gauges, valves and controllers) all enclosed in one unit. This type of pump reduces the overall maintainence and cost of the pumping station. The pumpout Tees will be located on the platform near the ventilation shaft which will allow easy access for maintenance plus the pumping stations will be far from personnel passage ways, see figure 10.

The pumpout Tees are placed in J1T so that any possible tritium leak into the wave-guide will pass through the pump and return the Tritium to J1T. Placing the pump near the J1T-J1D barrier also limits the number of particles that will upstream into J1D if there is a failure in the CVD window at the torus. In the case of a CVD window failure, there will be a gate valve between the pumping station and the pumpout Tee that will close to prevent leaking of Tritium from the torus into J1T.

The support structures for the pumpout tees have yet to be designed. Conceptual design was to use similar cradles as used for the ground floor passage in J1T, the support frame holding the cradles would be angled to compensate for the tilted wave-guide lines.

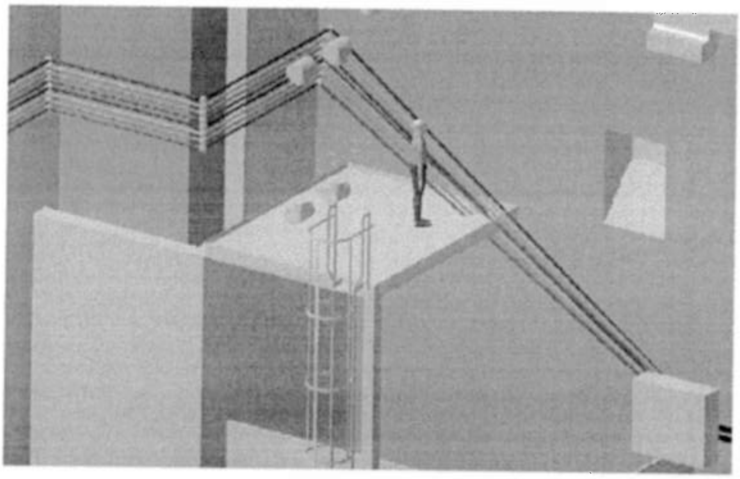


Figure 10 The Pumpout tees will be positioned in J1T just before the the J1T-J1D barrier. Acces to the pumping units is obtained from the existing platform found in the south-east corner of J1T.

The wave-guide lines along the south wall will be located at different distances from the wall. This allows a transition from the 2 by 4 array of wave-guide lines in J1T to a 1 by 8 array in the dogleg around the ventilation shaft and on the East wall. The supports for MB #5 and MB #6 (in the dogleg) would be one block unit assembling the 6 to 8 lines together in a stack assembly (see Figure 11).

5.3.2 East wall of J1T

The section along the east wall consists of straight wave-guide up until MB #7 which deviates the beam toward the torus. This last miter bend will be a Power Monitor miter bend that monitors the forward and reflected power in the wave-guide line. This location is ideal for the power monitor since it is close to the torus and avoids any potential injury from contact.

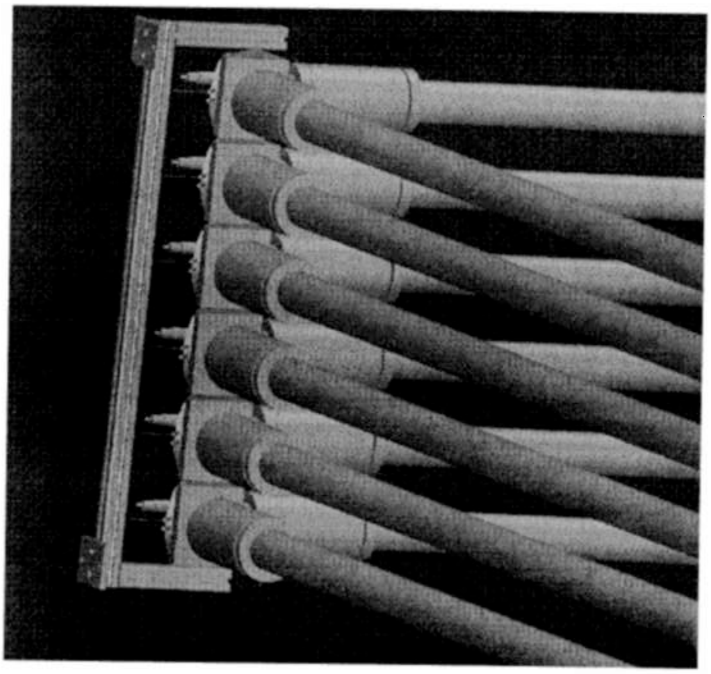


Figure 11 Miter bends #5 and #6 will be held in place by a 'sandwich-like' assembly as shown. The whole assembly will be adjustable vertically and horizontally for precission alignment.

5.3.3 Trestle Bridge

The section of wave-guide leaving the east wall and leading to the torus will be the only section of wave-guide that is required to be dismounted for full access to the launcher port. The wave-guides will be supported from a lightweight trestle structure, see Figure 12. 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 dismounting this section will involve disconnecting the line at either end (at torus and at east wall before MB #7) 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 dismounting this section of line.

The wave-guide elements included on the trestle bridge are: several pieces of straight wave-guide, a two-way switch, a DC break and miter bends (MB #7 and #8). The two way switch will allow the beam of one gyrotron to be either directed to the torus or to a neighboring gyrotron's transmission line and return to the calorimetric load. This switch along with the conditioning and calibration procedures is described in further detail in Sections 5.4.2. The DC break will be located just after the switch and provides isolation between the line and the torus. The wave-guide will be supported from switch (which is fixed on to the trestle bridge) and with cradles positioned near each end of the bridge.

The trestle bridge and associated support systems will be provided by CRPP. The structure will be made in two pieces to allow shipment of the bridge from Lausanne,

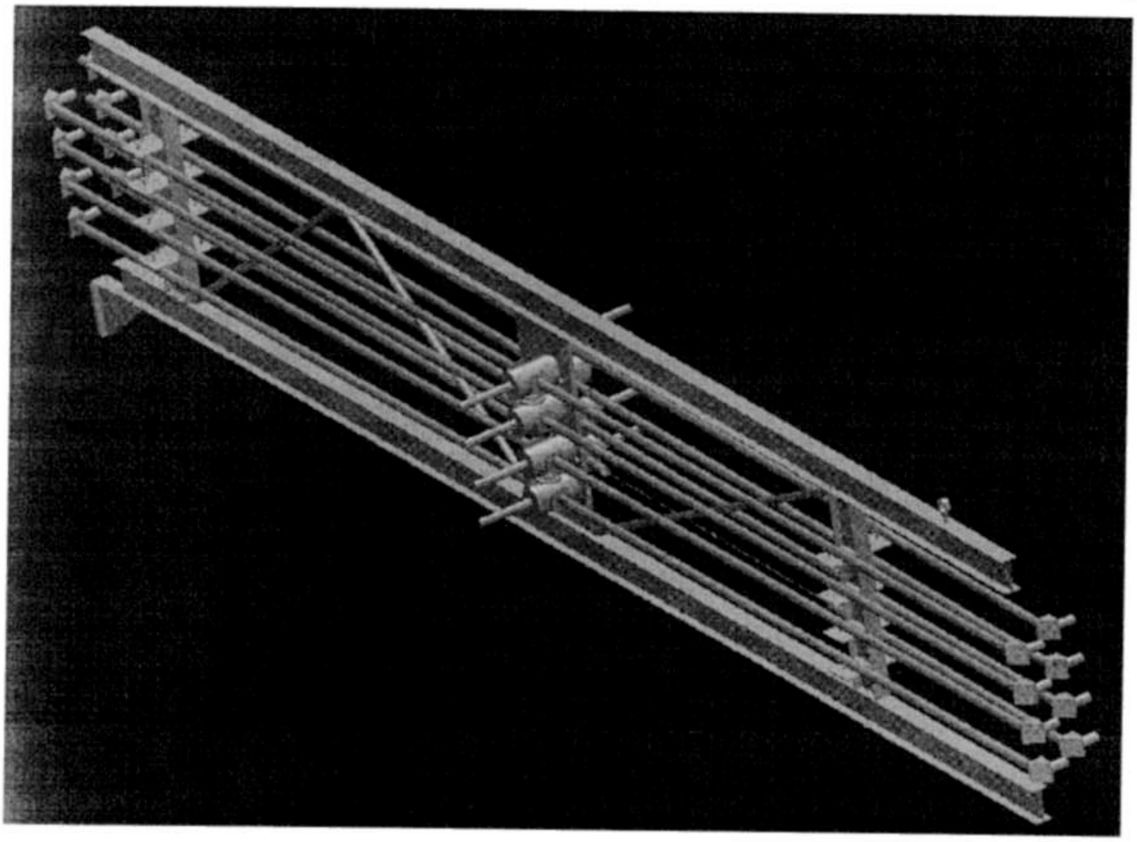


Figure 12 A trestle bridge structure will be used to support the waveguide from the east wall of J1T to the torus. The whole structure can be removed with in a few days for insertion of the Remote Handling Unit.

Switzerland to Culham, England. The Operator will provide a plate on the east wall for supporting the bridge. The west side of the trestle bridge will be supported from a hook already installed for the installation of the remote handling unit.

5.3.4 Wave-guide near Launcher

This section of the wave-guide line is the most complicated of the entire system. The wave-guide has to be designed to accommodate the torus displacements due to thermal cycles and disruptions plus this section includes the most expensive and fragile component, the CVD window. The wave-guide near the launcher has a dogleg formed from MB's #8 and #9 before entering into the launcher port, see figure 6. The dogleg allows passage around the KN3 diagnostic plus adds flexibility of the line to accommodate the torus displacement. The wave-guide section between MB's #8 and #9 (leg #9) bends to accommodate the radial displacement of the torus (17mm thermal, 16mm disruption). The wave-guide section preceding MB #8 will be unsupported for at least 1.5m that will bend to compensate for the toroidal displacements during disruptions (8mm). Both sections of wave-guide that bend will be sufficiently long enough to insure induced stresses are 80% less than the Yield strength of the wave-guide. Note the Yeild strength allows for >100,000 cycles before failure occurs.

After the straight section of wave-guide there is the double disk CVD window, MB #9, all metal gate valve and then entry into the torus. The wave-guide is fixed to the torus flange between the end of the straight section and the CVD window housing unit, this will limit the stressing and possible failure of the CVD disks when the torus undergoes displacement. All wave-guide elements after MB #8 will be supported by the support structure mounted on the launcher. The whole section is removed in one piece. The support structure on the launcher port is under the responsibility of FOM.

The wave-guide section between MB's #8 and #9 can be modified to change the connection between launchers and gyrotrons. For example if a launcher malfunctions, the wave-guide lines can be modified to connect the related gyrotron to a new launcher. (Two of the eight launchers are spare). Figure 13 illustrates an example of a malfunction in launcher #2. Since launcher #8 is one of the spare launchers and since the even numbered lines in this section are in the same plane, all of the even numbered lines have to be modified as shown. The procedure should take about a day and requires human intervention into J1T.

The inter region between the two CVD disks will be monitored for pressure changes which will indicate a possible leak from the torus vessel. This component is under the responsibility of FZK[11].

The gate valve between the CVD window and launcher will close in the event of a window failure limiting the flow of Tritium into the wave-guide line. Also the gate valve allows the changing of a window unit without affecting the torus pressure. The gate valve will be equipped with a pumping port that can be used to evacuate the space between the gate valve and the window-housing unit. The gate valve will be of all metal construction.

A section of the wave-guide after the gate valve is inserted into the torus vacuum chamber. This wave guide piece are included in the design of the launcher [12]. All elements after the CVD window-housing unit is under the responsibility of FOM. However, the items will be included on the Call for Tender for the transmission line and both CRPP and FOM will interact in writing the specifications of each element.

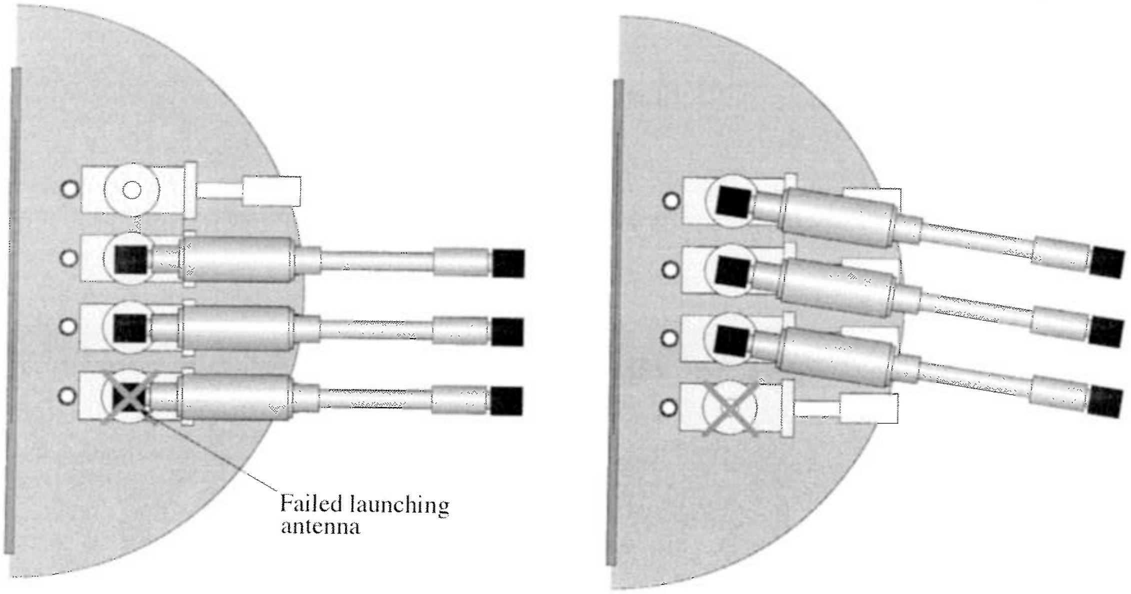


Figure 14 The waveguide leg #9 can be adjusted to change the connection between the gyrotrons and launchers. In the case shown Launcher #2 has malfunctioned and all even numbered lines are modified so that the launcher #8 can be used instead of #2.

5.4 Security and Operation Issues

The overall design of the transmission lines were strongly influenced in requirements for personnel security and for reliable operation. Some of these issues were briefly discussed in Section 4.1, this section will concentrate on the implications for the design and some of the alternatives which were considered to be implemented.

5.4.1 Tritium Barrier philosophy

The proposed wave-guide routing is designed with an option to maintain the two tritium barriers of the JET installation, i.e. torus vessel and torus hall. A schematic of the Tritium barrier philosophy is shown in figure 3.

At the torus vessel the wave-guide 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 be accessible for at least rough vacuum pumping before and after each opening of the torus.

There are three options for the in-line wave-guide barrier at the wall (second Tritium barrier) 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 this text assumes 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 wave-guide, the exhaust of the pumps in each MOU will be channeled back into J1T by a metal tube following the waveguide routing up to the ventilation shaft. This limits the worst-case scenario of a tritium leak into the wave-guide to the confines of the wave-guide, MOU, turbo pump and return line. An option to increase the security against tritium leaks exists by using a single or double disk CVD window at the barrier for an increase of 10 to 15% of the total cost of the wave-guide line. The CVD window can be added at this location for a minimal cost: a single disk for ~53k€ and a double disk for ~84 k€ (with Helicoflex™ seals).

5.4.2 Gyrotron-line conditioning and calibration philosophy

Incorporated in any ECRH transmission line system is the requirement to allow conditioning and calibration of both the gyrotron and the transmission line.

5.4.2.1 Gyrotron conditioning

From the experiences of gyrotron operation at CRPP, there are two types of conditioning procedures for the gyrotrons (neglecting initial conditioning at on-site acceptance testing): (A) after a long term of non-operations and (B) at the start of each day. Type (A) conditioning requires firing the gyrotron during several days, the initial pulse length is short and is slowly extended to full pulse lengths. This type of conditioning requires the use of a load (not necessarily a calorimetric load) connected to the gyrotron. Conditioning of this sort occurs less than once every other year.

Type (B) occurs on each day of operation, a few short pulses are fired to insure that the operating beam current in the gyrotron is correct and to provide a few conditioning pulses to recouperate the gyrotron's condition after the pause from the last use. This procedure requires about 30min of operating time and only needs a load capable of absorbing full power but at very short pulse lengths (~200ms).

In both types of conditioning procedures the gyrotrons have to be connected to an evacuated load. Since type (A) conditioning occurs rarely there are two types of loads to be purchased for the gyrotrons, a short pulse load connected to each pair of gyrotrons and one single long pulse load which can replace the short pulse load for type (A) conditioning of any given launcher. The purchase of several short pulse loads and only one long pulse load represents a cost savings in the price difference between a short and a long pulse load (~30k€ vs. ~115k€). A total savings of about 30k€ per transmission line.

5.4.2.2 Gyrotron Calibration

The design of the transmission line should allow for the measurement of the output power from the gyrotron. This procedure is usually performed at the on-site acceptance test and periodically through the life of the gyrotron (typically once every two years or so). To measure the output power of the gyrotron, a calorimetric load is connected as close to the output of the MOU as possible, to avoid power losses from wave-guide elements. The above solution of purchasing one single long pulse load would allow the measurement of each gyrotron's output power during the same procedure as the type (A) conditioning.

5.4.2.3 Line conditioning

CRPP's experience with the nine evacuated 63.5mm corrugated wave-guide installed on TCV operating at 0.5MW is that the first pulse operating into the transmission line after it has been at atmosphere will sometimes result in breakdown on one of the miter bend mirrors. The break down does no damage to the transmission line or miter bend mirror and the succeeding pulse is usually successful. Yet if this first shot is fired into the tokamak with a plasma it is usually a failed shot due to the quick shut down of the ECRH pulse. This event can be avoided by performing a few short conditioning pulses in the line either directly into the tokamak or into a load (The conditioning of the line can be performed up to the trestle bridge structure but not the miter bends #8 and 9). Firing into the tokamak without a plasma can be dangerous to sensitive equipment since the beam will scatter throughout the chamber due to low absorption on the torus wall. Note that a given line will rarely be brought up to air, typically only after a tokamak opening.

5.4.2.4 Line calibration

Once the line is installed it should be calibrated in order to know the delivered microwave power to the launcher. This procedure requires placing a full pulse calorimetric load at the end of the line and measuring the delivered power for each transmission line. However, with the proposed switching system described in the following section, the delivered power can be measured by firing a pulse down the line up to the launcher and then return via a neighboring line. The signal from the power monitor miter bend can be cross-calibrated with these shots. The calibration can be performed without requiring human access to the J1T zone.

5.4.3 Proposed switching system

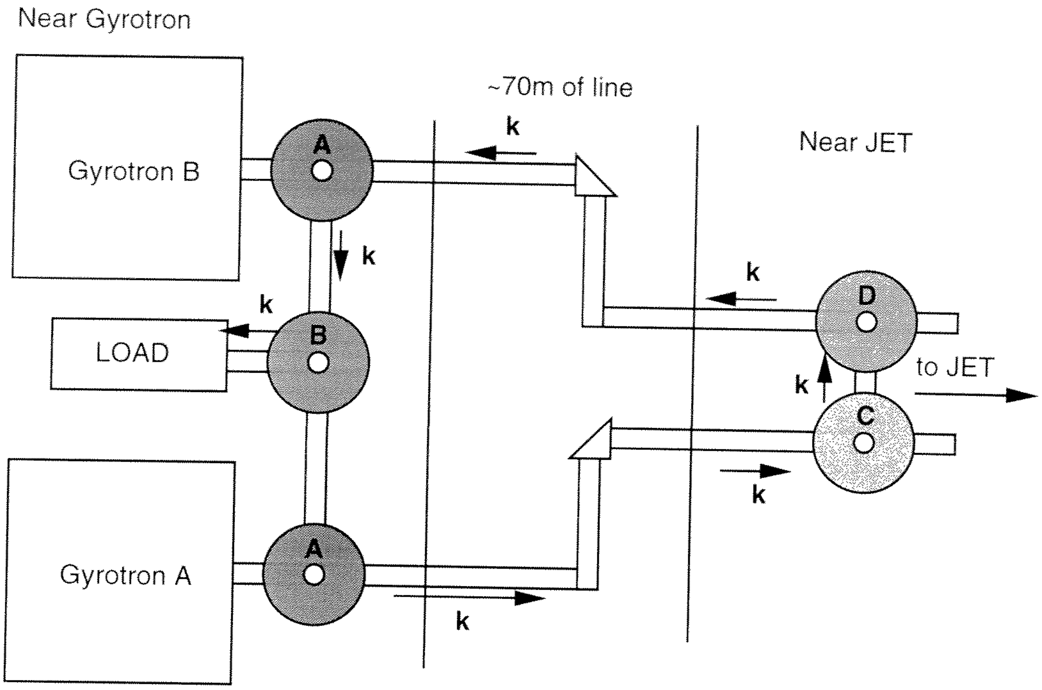
The ideal solution for all of the conditioning and calibration of both the gyrotron and line was modelled from the ECH system envisioned on W7-X stellarator[13]. The quasi-optic transmission lines on the W7-X stellarator have a mirror system which allows a gyrotron to fire either into a load near the gyrotron, through the whole length of the line and then reflected back down a neighboring line into the same load or into the stellarator[13]. This concept has been adapted to the JET wave-guide line using five in-line vacuum compatible switches per each pair of gyrotrons, see figure 14, and allows the conditioning and calibration of both the gyrotron and wave-guide line nearly up to the tokamak without requiring manned access to J1T. The switching network can easily be applied to the ITER device which could benefit from a copletely remote conditioning and calibration system.

At the output of each gyrotron there is a three-way switch, which directs the beam either toward the tokamak, directly to the load or to the load via the return path from the neighboring wave-guide line. In the direction of the load there is a two-way switch, which allows the sharing of a load between two gyrotrons and selects which gyrotron fires into the load. Near the end of each line is a two-way switch, which directs the beam either toward the tokamak or into the line of the neighboring gyrotron to return to the load. This switching network increases the overall costs of a typical line by ~60k€ but provides the conditioning and calibration of the gyrotron and transmission line up to the launcher without interfering with the tokamak operation.

Also a gate valve is incorporated in the three-way switch just before the load to all switching between the short and long pulse loads without effecting the vacuum in the transmission lines.

5.4.4 Remote Handling System

The wave-guide and launcher are installed in the port that is used by the remote handling assembly for manned access inside the tokamak. To clear the entry for the remote access unit a section of the wave-guide must be dismounted and the launcher removed. The trestle bridge described in Section 5.3 is designed to allow quick dismantling of the transmission line near the tokamak. The region that must be cleared for entry of the remote handling unit includes all wave-guide pieces from the power monitor miter bend to the launcher, inclusive. This section describes the removal and re-installation of the wave-guide for the entry of the remote handling system.



Switch A: S, L, R positions available
Switch B: L, R, positions available
Switch C: S, L positions available
Switch D: S, R positions available

Figure 15 Schematic of the switching network incorporated in each line. A short pulsed load (<200ms) is planned to be used which can be replaced with a CW load for gyrotron conditioning and calibration. The switches nearest the gyrotron allow directing the output to the load or torus. The switches near the tokamak direct the beam to the torus or to the load via the return path along the neighboring transmission line.

5.4.4.1 Removal of the trestle bridge

The Trestle bridge unit is designed to minimize the complications involved in disconnecting and reconnecting the wave-guide. The overall process involves installing scaffolding at the east wall and at the launcher. The coupling unit before the power monitor (direction gyrotron) and the coupling between the wave-guide in leg #9 and MB #8 is removed. Then the overhead crane is connected to the trestle bridge such that there is no slack in the cables, the bridge is disconnected from the east wall and on the hooks used for the boom, and the whole assembly is removed. Once the space is clear of the bridge it may be useful to remove one wave-guide section from each line before the power monitor to insure the wave-guide is not damaged by the remote handling unit.

A location to store these items will need to be found. Preferably, the Operator can be responsible for the storage location.

5.4.4.2 Removal of the wave-guide near launcher

The CVD window housing unit, gate valve, MB #9 and the waveguide in leg #9 are to be removed in one block unit before the launcher assembly is removed. All wave-guide pieces will be held in place by the support structure attached to the launcher port. The gate valves will be disconnected from the wave-guide feedthroughs on the launcher port. Then the whole assembly is supported by a crane before dismounting the support from the launcher flange. The gate valve, MB #9 and part of the CVD window will need to be sealed to insure containment of any Tritium (wave-guide section after the CVD window is potentially contaminated with Tritium). The other end of the assembly will not contain Tritium since the double disks provide a shield from the torus vacuum. The end should be sealed sufficiently to or event dust from entering the pieces.

With the removal of both the trestle bridge and the CVD window section the KN3 diagnostic and the launcher can then be removed.

5.4.4.3 Re-installation of the trestle bridge

The trestle bridge should be installed first before the CVD window wave-guide section. The bridge should not be installed until after the launcher and KN3 diagnostic have been re-installed. The bridge unit can be brought in by the overhead crane and positioned on the support frame at the east wall and supported at the launcher by the hooks. The bridge should be bolted in place before the crane is removed. The wave-guide supports on the bridge will allow slight re-alignment (±2cm on either end to realign to the connecting pieces of wave-guide. Once the bridge is in place the wave-guide pieces before power monitor (MB #7) can be reconnected.

5.4.4.4 Re-installation of the wave-guide near launcher

Once the bridge is in place the section of waveguide including the CVD window can be re-installed. The flange matching to the gate valve is a rotatable flange for facilitating the re-alignment of this section of waveguide with MB #8. This coupling should be adjustable until the whole section of wave-guide is in place (this insures that the wave-guide piece between MB #8 and the CVD window housing can be aligned with both the wave-guide on the trestle bridge and to the CVD window housing unit. Once the CVD section is installed, the coupling section linking the trestle bridge to the CVD window should be installed and tightly sealed. The final step is to tighten the seal at the gate valve.

Before opening the line to the torus pressure the space between the gate valve and CVD window unit should be differentially pumped.

6 WAVE-GUIDE ELEMENTS

This section is devoted to describing the wave-guide elements to be used on the transmission line. Detailed specifications of each element have not been included in this document but were planned for the Call for Tender document, which was never produced. The items are presented in order of their appearance in the line leaving the MOU and approaching the Tokamak.

Since the transmission line will be operating under high vacuum and at high power conditions, all components are required to be free from surface imperfections such as burrs, pits, dirt, oils, and water vapor. All elements must under go sufficient cleaning procedure to insure reliable operation under high vacuum and at high power. The cleaning procedures will be requested by each potential manufacturer.

Unless otherwise specified any given wave-guide element must be designed to insure sufficient radiative cooling via the local environment with a maximum temperature of $\leq 40^{\circ}$. This includes the following items: DC break, coupling systems, standard and special sized wave-guides, in-line bellows, and pumpout Tees. Wave-guide elements that can be water-cooled are: miter bends, switches, loads, gate valves and power monitor miter bends.

All elements unless otherwise stated must be designed to allow a spacing between the axis of two elements of 150mm for any configuration of orientation. Wave-guide elements, which are not required to meet this requirement, are: Loads, switches, pumpout Tees and the back of the power monitor miter bend within the plane of the bend.

The power handling requirements of all components must allow 2.0MW CW propagation for the operating frequencies of both 113.3GHz ±1GHz and 170GHz ±1GHz. Elements which do not meet the two operating band widths must be specified by the manufacturer. An option for modifying the elements with passive cooling to extended 2MW operation would be included in the Call for Tender.

6.1 MOU-Transmission line interface

The gyrotron manufacturer supplies the Matching Optics Unit (MOU), which is used to couple the output beam to the wave-guide and to adjust the beam's polarization for optimum coupling to the plasma. The internal mirrors of the MOU can be tilted to adjust for optimum alignment into the 63.5mm corrugated wave-guide. The location of the start of the wave-guide will be located at the same location for all gyrotrons. The flange on the output of the MOU will be either a CF100 or CF160 with the possibility of either Helicoflex seals or copper gaskets. The MOU system must have a bellow located either between the gyrotron and the MOU or the MOU and the wave-guide. This allows for a decoupling of the rotation of the gyrotron about its axis and the direction of the output wave-guide. Without the bellows the long section of the wave-guide leaving gyrotrons

#4, 5, 6, 7 and 8 would require a very precise rotation (<0.01°) of the gyrotron-MOU-line assembly to insure that the location of MB #2 is in the correct north-south location

6.2 DC break

An in-line DC break with isolation voltage of 5kV will be attached directly to the MOU. This element provides voltage isolation between the gyrotron and the transmission line. Otherwise there would be a risk that the line could be charged during a gyrotron pulse, which would present a health risk to any personnel coming in contact with the line. The DC break allows a complete isolation and a separate grounding of the line from the gyrotron.

On one end of the DC break will be either a CF100 or CF160 SS flange (flange size is determined by Gyrotron manufacturer specifications). The other end of the DC break will be the standard coupling joint of specified by the wave-guide manufacturer. 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 ~1.9W.

6.3 Coupling system

The standard coupling joint of the wave-guide manufacturer must insure that the two consecutive wave-guide pieces are aligned (the two components must be coaxial). This also implies that the coupling should be useable to align to any two consecutive elements. The coupling system must be uniform for all wave-guide elements unless otherwise specified. For each wave-guide element purchased there will be at least one complete coupling unit delivered.

Since the wave-guide will be evacuated the coupling joint should also insure that the joint between the two wave-guide pieces insures a low leak rate. The sealing unit must be a metal seal and insures a good electrical contact between the two pieces. The sealing unit should provide sufficient pressure to compress the joint and allow the wave-guide pieces to be connected and sealed a multiple of times. It is preferred that the coupling system is uni-sex such that both ends of the wave-guide elements are identical and the orientation of the wave-guide pieces and coupling system can be interchanged.

6.4 Wave-guide

The standard wave-guide length should be ~2.1m in length and machined from one piece. Lengths of all standard wave-guide pieces will be within ±1mm. The ends of each piece should be identical (uni-sex coupling system) unless otherwise specified. The exterior of the wave-guide surface must be uniform and co-axial to the wave-guide bore to within sub millimeter precision. The exterior surface will be used for alignment and support of the wave-guide.

Some of the exact dimensions of the wave-guide are left up to the discretion of the manufacturer. However, all dimensions will be specified in the responses from the Call for Tender. The exact shape of the corrugations will be left up to the manufacturer; preference will be toward corrugations that are not helical cut grooves. (Helical grooves result in a polarization rotation of the microwave beam along the length of the wave-guide).

The wave-guide must be flexible to allow a certain amount of bending to compensate for torus displacement during thermal cycles and disruptions. For a 1.5m section of wave-guide with the two ends connected to fixed wave-guide elements, the two ends must allow a displacement of up to 19mm without undergoing plastic deformation for at least 100,000 cycles.

Some non-standard length wave-guide pieces will be needed in assembling the transmission line. The exact length of these pieces will not be known until after the contract between with the manufacturer has been signed. The manufacturer will be asked to machine several pieces with the exact length to be specified by a given date after signing. A few pieces in the longer wave-guide runs will have to be cut and machined by either CRPP or the Operator at the time of assembling the line. The manufacturer will be asked to provide detailed design drawings of the wave-guide ends to allow either association to perform the machining.

The ohmic attenuation of the corrugated wave-guide should not exceed 0.05dB/100m at 113 GHz and 0.015dB/100m for 170 GHz. For a typical line length of 72m this corresponds to 0.83% and 0.25% for the two frequencies

6.5 Switch

Three types of switches will be required for the transmission line. The purpose of each switch is described in Section 5.4.2. All switches must allow operation in either direction at the rated 2.0MW CW operation. It must be possible to manipulate the switches under vacuum and be controlled remotely. The normal operation of the switch is with the beam passing straight through the switch. In this case the insertion losses must be small <0.1%. In the diverted operation the switch will send the beam ±90° (precision of ±0.05°) with an insertion loss of <1.0%.

The three types of switches are: Three-position switch, left handed two-position switch and a right-handed two-position switch. The handedness of the switch is defined by the direction the beam is deviated as looking into the switch at the input and the actuator pointing upward, see figure 14.

6.6 Calorimetric Loads

The calorimetric loads will be used for conditioning the gyrotrons and the transmission line in situ. A single load will be shared between two gyrotrons; only one of the two gyrotrons can fire into a load at a time. Two types of loads will be used: a short pulse (~200ms) and long pulse (CW operation). The loads will be located on the gyrotron platform; the choice of firing into the load or tokamak is made via the vacuum switch described above. Normally, the short pulse load will be attached to the transmission line and is used for daily operation of the gyrotron on to the tokamak. Pulse lengths from a few hundred microseconds up to ~200ms are used at the start of an operating day to insure that the gyrotron's beam current is correct. Longer pulse lengths are not necessary. The second load is a CW load, which will be used for conditioning and callibration of the gyrotron during acceptance tests and after long periods of in-activity. The short pulse load will be replaced by the CW load when necessary for gyrotron conditioning or calibration. Only one or two CW loads will be purchased. All loads will be compatible for 2MW operation.

Aside from the pulse lengths the requirements of the two loads are the same. Both loads should be able to measure the input power to within ±5% and operate at least 2.0MW (for ITER applications). The VSWR of both loads is ≤1.3 and the loads are to operate in any orientation.

Flow and temperature measurements are included with the purchase of both loads. Calibrations of these measurements are to be included for measuring the input power. All necessary security interlocks are to be included to insure safe operation of the load. All interlocks and measures will be accessible for remote operation.

6.7 Miter bend

The miter bend is used to change the direction of the beam by 90° (±0.05°). For the operating frequency (for both ITER and JET) and the chosen wave-guide diameter a flat copper mirror is used to deviate the beam. Two small holes are drilled through the mirror and fiber optic arc detectors are attached to the back of the mirror. One arc detector 'views' in the forward direction, the second in the backward direction. The arc detectors monitor the wave-guide line for breakdown, in the event of break down the detectors observe the light and then interrupt the pulse on a fast time scale (<10μs). No damage occurs to the mirror surface under vacuum conditions during a breakdown in the line.

The miter bends are the lossiest items in the transmission line; loss on each miter bend is a sum of the ohmic and mode conversion losses. The ohmic losses are estimated at 0.12% of the forward directed power (average between E and H plane bends) for 113 GHz and 0.15% for 170 GHz[14, 15]. The mode conversion losses are 0.47% and 0.26% respectively for the two frequencies. Half of the power converted to other modes will be in lower order modes, which will be transmitted through the line; the other half of the power is converted to higher order modes, which will be attenuated in the wave-guide. The following table summarizes the losses in a series of 9 miter bends:

Type of losses	# of MBs	% per MB 113GHz	% total 113GHz	% per MB 170GHz	% total 170GHz
Attenuated in T-line	9	0.40	3.6	0.33	~3.0
Mode converted (Transmitted)	9	0.23	2.1	0.13	~1.2
Total losses	9	0.63	**~5.7**	0.46	**~4.1**

The miter bend mirrors will be water-cooled, flows rates deterimined from the manufacturer. Microwave coupling through the holes of the arc detectors are <65dB.

6.8 In-line bellows

In-line bellows are needed in long sections of wave-guide runs to compensate for thermal expansion and contraction of the line from thermal variations of the room temperature. The longest straight section of line is in J1D which is ~19.5m long and fixed on one side by the barrier between J1T and J1D. With a thermal expansion of the wave-guides of $23*10^{-6}$/C, and a possible ±15° temperature variation in J1D, the line will vary in length up to ±7mm. The in-line bellows would compress/expand to avoid the displacement of the miter bends on either end of the wave-guide run. Sections of wave-guides that are much smaller and result in only a small change in length (<2mm) due to temperature fluxuations will not require in-line bellows.

The inner diameter of the bellows is corrugated and should allow for +5mm to –30mm of length variation. The overall length of the bellows is <400m and the maximum force for full compression or expansion should not exceed 600N. The associated insertion losses should not exceed 0.1%.

6.9 >4m wave-guide

A >4m section of wave-guide will be needed to pass through the barrier between J1T and J1D. The diameter of the hole through the barrier should be kept as small as possible for the neutron shielding. The wave-guide will pass through a steel tube (with ~100mm diameter) with the interspace filled with polyeurithane beads. A normal coupling unit would require a hole of ~130mm, the diameter of the coupling unit is ~120mm. Two wave-guides could be held together with a special coupling unit or welded to form a >4m section of wave-guide. In either case the outer diameter of the special coupling should not exceed 90mm, this insures that the waveguide and coupling unit can be inserted into the steel tube (ϕ=100mm) which traverses the barrier. Precision alignment between the two wave-guide pieces must be maintained.

An end plate will be added on the J1T side to seal the passage around the wave-guide to prevent leakage through the hole into J1D. Design would be determined with the Operator.

6.10 Gate valve @ barrier wall

An all-metal in-line gate valve will be placed on the J1T side of the barrier between J1T and J1D. This valve maintains the integrity of the tritium barrier of the concrete wall in case of CVD window failure. If the inter vacuum space between the two disk changes this gate valve will close (closing in a few 100's of milliseconds) to prevent the leakage of tritium into J1D. Also the gate valve will allow the isolation of the vacuum space of J1T from J1D. The gate valve will not have an auxiliary pumping port, the J1D side of the transmission line can be pumped via the MOU at the gyrotron, and the J1T side can be pumped from the pumpout Tee a few meters away from the gate valve. The valve will be mounted as close as possible to the barrier wall. The gate valve will close automatically if the compressed air is lost.

6.11 Pumpout Tee

The wave-guide will be pumped via two pumping systems: MOU and an in-line pump out Tee. Position of the pumpout Tee will be as close as possible to the barrier, in case of a CVD window failure the tritium would be first pumped by the pumpout Tee before up-streaming through J1D to the MOU. An all-metal gate valve and a dry-vac turbo pump will be attached to the pumpout Tee. The gate valve will be a part of the tritium security loop, if the CVD window fails; this valve will close after the gate valve at the barrier wall. The exhaust of the turbo pump will be channeled to the tritium exhaust stack in case a complete failure of the gate valves to close.

The pumpout Tee evacuates the transmission line via a gap of a few millimeters in the wave-guide. This gap allows sufficient pumping conductance to keep the maximum pressure in the line below 10^{-5} mBar yet is small enough to avoid significant power leakage into the pumping tee unit or mode coupling of the beam across the gap.

6.12 Power monitor miter bend

The power monitor miter bend will monitor both the power in the forward and reflected microwave beams. The power is coupled through several holes smaller than cutoff drilled into the back of the miter bend mirror. The radiated power through the holes is coupled to two rectangular horns and detected on low power microwave diodes. Typical coupling values are of the order of ~80dB and a directivity of ~20dB. The calibration of the power monitor is performed in situ using the switching network described in section 5.4.2, which permits the gyrotron beam to be fired down the line to the power monitor and then back to the load. The signal on the diode can be cross-calibrated to the power measured in the load. The power monitor is sensitive to the input polarization; this can be accounted for by calculating the polarization at the power monitor's from the polarizer rotation angles in the MOU.

6.13 CVD window housing unit

A two CVD disks are installed at the end of the transmission line just before the entrance into the launcher. These disks provide a tritium barrier at the torus while providing low loss transmission of the microwave beam. The vacuum between the two disks is monitored continuously to insure the isolation between the wave-guide and torus vacuum.

FZK will be responsible for the CVD window-housing unit. The flanges on either side of the window unit will be CF-160 flanges with either copper gasket of Helicoflex™ seals. No detailed specifications are included in this text for the window unit since it will not fall in the scope of delivery of the transmission line.

6.14 Launcher Miter Bend

A miter bend is placed between the CVD window-housing unit and the gate valve on the launcher entry port. The miter bend is equivalent to the standard miter bend except that the flanges on both sides are CF-160 flanges rather than the wave-guide manufacturer's coupling system. Either copper gasket or Helicoflex™ seals can be used on the CF-160 flanges. The arm of the miter bend toward the CVD window will be as small as possible while the arm toward the gate valve will be about 200mm long. This later distance is needed to provide clearance between the gate valve and the CVD window-housing unit. This unit is under the responsibility of FOM but will be included in the *Call for Tenderer* of the transmission line, which is under the responsibility of CRPP.

6.15 Gate valve @torus

An all-metal in-line gate valve will be placed between the launcher and the CVD window-housing unit. The gate valve closes in the case of CVD window failure, which then isolates the transmission line from the torus vacuum. The gate valve also allows servicing of the CVD window-housing unit without affecting the torus vacuum.

The gate valve will have an auxiliary pumping port access which will allow pumping the vacuum inter space between the gate valve and CVD window upon installation of the transmission line. In normal operation the gate valve will be left open and this space will be pumped via the torus pumping stations. Either copper gasket of Helicoflex™ seals can be used on the gate valve flanges. The valve will be controlled locally or remotely and operate with compressed air. The valve will close if there is a failure of compressed air. This unit is under the responsibility of FOM but will be included in the *Call for Tenderer* of the transmission line, which is under the responsibility of CRPP.

6.16 Launcher wave-guide

Two sections of wave-guide will be incorporated within the launcher. The first is a SS wave-guide piece welded on to the flange of the launcher and extends into the launcher chamber (~300mm) and outward to the gate valve. The second piece is standard wave-guide piece that is mounted inside of the launcher. The exact specifications of both of these pieces are to be determined by the launcher design team and then included in the *Call for Tenderer* associated with the transmission line.

7 TRANSMISSION LINE LOSSES

There are several sources of losses in transmitting high power microwave beams through highly overmoded circular corrugated wave-guide. The six principle losses are described in this section which include:

- Coupling into the wave-guide
- Ohmic attenuation in the line
- Miter bend
- Wave-guide gaps
- Wave-guide sagging due to gravity
- Misalignment of wave-guide supports

Each of these sources will be addressed individual in this section. A "loss" is considered as any power removed from the principle-transmitted mode, HE_{11}, either as an ohmic attenuation or in conversion to other modes. The power converted in other modes is either in very high order modes, which are quickly attenuated over short distances in the wave-guide (~20 cm); and lower order modes, which are poorly attenuated. A large fraction of the lower order modes are transmitted through the transmission line. It is useful to distinguish between the lower and higher order modes because at CRPP about 70% of the lower order modes was transmitted through the transmission line and launching antenna (4 mirrors) and remained with in the fundamental mode's envelope in free space. This transmitted power, therefore, is useful for both heating and NTM stabilization in which the power density is important. In considering the different losses of each source, the higher order modes will be included with the ohmic attenuation since the power coupled to these modes are fully damped in the wave-guide.

7.1 Coupling into HE_{11} wave-guide

The beam coming from the gyrotron is specified to have a mode purity in the TEM_{00} of 97%. 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} wave-guide and a majority of the power in these modes is expected to be transmitted to the end of the wave-guide.

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 wave-guide. The delivered power of the gyrotron is measured after the entrance to the wave-guide, so the 1.4% of the power apertured by the wave-guide is a hidden loss. Therefore, the delivered power of the 'tube' as measured in the wave-guide (1.0MW) is comprised of >96.4% HE_{11} and <3.6% other modes, this is illustrated in figure 15.

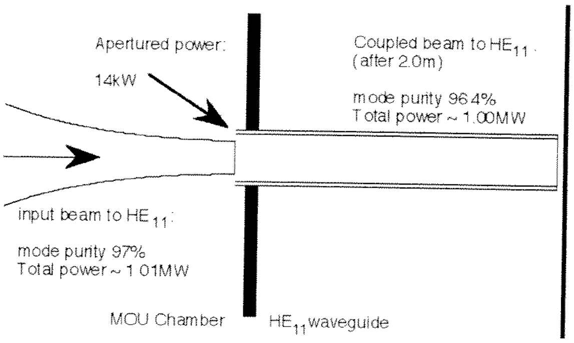


Figure 15 Mode purity and total power of beam before and after wave-guide entrance.

7.2 Line attenuation

The attenuation per 100m of wave-guide is shown in the following Table for the four wave-guide diameters. The average length of the JET-EP transmission lines is 71.2m; the attenuation in each line is calculated for this length, the 63.5mm line will have 0.5% ohmic losses.

	31.75mm	**45mm**	**63.5mm**	**88.9mm**
Attenuation dB/100m	0.24	0.08	0.03	~0.01
Average length	71.2m	71.2m	71.2m	71.2m
Attenuation in line	3.9%	1.3%	0.5%	.16%

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

The larger diameter wave-guides have a much lower attenuation compared to the smaller wave-guide as seen from the above. However, this advantage is counteracted by the mode conversion, which occurs from bending of the wave-guide either from misalignments, or sagging due to gravity, see Sec. 7.5 and 7.6.

7.3 Miter bends

The miter bends elements have the highest losses (both ohmic and mode conversion) of the entire line. The ohmic attenuation is due to losses of the beam incident on the mirror. These losses are dependent on the conductivity of the mirror at the particular frequency of interest and the polarization of the beam. Introducing a phase correcting mirror in the place of a flat mirror depending on the frequency and wave-guide diameter can reduce the mode conversion losses. The use of a phase corrected mirror for the 63.5mm wave-guide at either 113.3 or 170GHz has a negligible reduction of the mode converted losses. A flat mirror maintains the broad operating band of the wave-guide line for the two frequencies of 113.3 and 170GHz.

The ohmic attenuation ranges from 0.08% (H-plane) to 0.16% (E-plane) at 113.3GHz. For O-mode injection into JET there will be 2 H-plane and 5 E-plane and 2 bends will be half H-plane half E-plane, therefore the total ohmic attenuation in the 9 bends is ~1.2%. In the case of 170GHz operation on JET, the ohmic losses would be slightly higher, 0.10 (H-plane) and 0.20% (E-plane) for a T-line total of ~1.5%

The power converted to other modes in a miter bend is divided between 50% of low and 50% of high order modes. The higher order modes (25% forward and 25% reflected) will be quickly attenuated in the wave-guide, while the majority of the power in lower order modes (all forward propagating) will be transmitted through to the launcher. The total power coupled to other modes due to one miter bend for 113.3GHz (170GHz) is 0.47% (0.26%).

The power lost from the fundamental mode at 113.3 GHz in the transmission line due to the nine miter bends is 5.43%, with 3.31% being attenuated and 2.12% coupled to low order modes. Power lost at 170GHz operations is 3.67% attenuated and 1.17% coupled.

The current design of the transmission line has 8 miter bends and 1 power monitor miter bend. The power monitor miter bend will have equivalent losses as the miter bends described above. A modified line would be proposed which removes two H-plane miter bends by avoiding the dogleg around the ventilation shaft in the South East corner of J1T. This would reduce the losses by 0.8% (attenuated) and 0.47% (coupled to lower order modes).

7.4 Wave-guide gaps

In each line there will be three elements with small gaps introduced between two wave-guide pieces. The DC breaks have a gap of ~3mm which provide isolation of the transmission line from the gyrotron and the tokamak. The vacuum switch has a small gap (~1mm) for the rotation of the center block between the 'through' and 'diverted' positions of the beam. The third element is the pumpout tee which provides pumping access into the wave-guide via a ~1mm gap. When a beam propagates across the one of these gaps it expands and has a curved wave front when it arrives at the next wave-guide entrance. As the beam re-enters the opposing wave-guide, the beam is apertured and coupled back into the HE_{11} and other modes. The fractional power, P_{gap}, lost due to the gap is given by[15]:

$$P_{gap} = 1.6 \cdot \left(\frac{L}{ka^2} \right)^{3/2}$$

where a is the wave-guide radius, k is the beam's wave number and the L is the distance across the gap. For the largest gap (3mm in DC break) the lost fractional power is ~0.01%, a negligible loss.

7.5 Wave-guide sagging and misalignments

Bending of the wave-guide causes a coupling of power from the fundamental mode to other modes. The two principle sources of bending are the gravitational sag of the wave-guide between two supports and the misalignment of two consecutive supports. Minimization of both of these losses can be achieved by optimizing the distances between the supports so that the minimum power is coupled to other modes. Support spacings too short will minimize the gravitational sag but will have very large mode coupling due to small misalignments between supports. Likewise, the misalignments between two supports become negligible over long distances, but the sagging increases. There is some optimum range of spacing depending on the beam's frequency, the wave-guide diameter and the precision in support alignment.

The mode conversion in the wave-guide due to gravitational sagging as a function of distance between supports was calculated for an 'average' line of 71.2m and is shown in figure 5. Note the support spacings were kept constant at the specified distance through the whole line, in reality the supports spacings would be kept non-regular. The peaks near support spacings of 3.5, 7.0 and 10.0m correspond to beat wavelengths between the fundamental mode and a lower order mode. Support spacings at these lengths will be avoided.

A similar calculation was performed for the fractional power converted to other modes for a 0.5mm displacement between supports. The precision in alignment can easily be achieved based off of the experience from mounting the equivalent transmission line at CRPP. The method of aligning the wave-guide will be addressed in Sec. 8.2. The fractional power converted to other modes increases as the support spacing decreases as shown in figure 5. The wave-guides are only constrained in a vertical plane; the supports allow horizontal displacement in order for the wave-guides to self align.

A combination of the calculated losses from the gravitational sag and the misalignment reveals a minimum with support spacings between 4 to 6m. The next step in the design would have been to choose supports over this range according to the physical constraints within J1D and J1T, using non-uniform lengths between supports. Also, the misalignment error would be randomized and the total losses recalculated for the different configurations of support spacings. The support locations, which provided minimum losses, would then be chosen. Even in the above case the total fractional power converted to other modes due to gravitational sag and misalignment was <0.1%, which is negligible.

7.6 Total losses

The following Table lists all of the significant transmission losses that can be expected in the JET line. The overall transmission efficiency of 90.6% represents the percentage of power remaining in the HE_{11} mode. Approximately two thirds of the lower order modes will be transmitted into the plasma with a relatively narrow beam envelope and will contribute to localized heating. Thus the overall efficiency of the line of the delivered power will be ~ 94.5%.

	Ohmic + higher order modes	**Low order modes**
TEM_{00} to HE_{11} coupling	-	3.6%
Wave-guide attenuation	0.5%	-
Miter bends	3.1%	2.1%
Gaps in Wave-guide	<0.01%	<0.01%
Sag & misalignments	-	< 0.1%
Total losses from HE_{11}	~3.6%	~5.8%

Sum of the transmission losses in an average 71.2m wave-guide line. Note that the delivered power to the plasma will be higher than these values, based off of power measurements performed at CRPP, a majority of the lower order modes were transmitted through the line and launcher and remained within the TEM_{00} envelope and therefore contributes to the localized heating of the ECH beam.

8 MISC. ITEMS

This chapter is devoted to a few auxiliary systems/procedures (for example: support structures, cooling circuits and alignment procedures) that are a part of the wave-guide transmission line. The intent is to give a brief description of how these items were envisioned for the final project at the time of the cancellation of the project in February 2002. The concepts presented here have not been given to the JET Operator for acceptance and, therefore, would be subject to many alterations if the project had continued. The list is not complete and is limited due to time constraints in producing this document.

8.1 Support structures

Wave-guide support structures are needed to position the wave-guide precisely and maintain the alignment of the line during the lifetime of the JET-EP ECRH project. The support structures were designed from the experience gained at CRPP, working with this same wave-guide diameter. Where possible the support structures were simplified to reduce cost as long as the mounting accuracy was not sacrificed. Also included in this section is how the supports are to compensate for the torus displacements during vessel thermal cycles and plasma disruptions and a brief description of the flexibility in changing wave-guide line to re-route a wave-guide of a given gyrotron to a reserved launcher in case a launcher fails.

Several types of support structures were envisioned for the wave-guide line. The principle supports are for the miter bends and the wave-guide lines. In mounting the transmission line the supports will be installed first. Then the miter bends of the first line will be mounted and aligned. The miter bends are aligned using a laser placed coaxially in the wave-guide arms with the beam projected to either the preceeding or following miter bend. Once two consecutive miter bends are aligned, the wave-guide supports between the two miter bends can be aligned relative to the laser beam. Once all of the supports are aligned the wave-guide can be mounted.

The different types of support structures are described in more detail in the following sections. The majority of the support structures were planned to be made by CRPP.

8.1.1 Miter bend supports

There are 9 miter bends per transmission line. The first and last three miter bends (#1,7,8,9) are free floating, supported via the wave-guide line. The rest of the miter bends will be mounted in an assembly such that all of the miter bends in a line are mounted together. Each miter bend assembly will be constructed to allow ±20mm variation in the positioning of the miter bends assembly. Once all the miter bends of the first line has been mounted and aligned all of the remaining miter bends in the other lines can be mounted and aligned relative to the first line.

Only one type of these support assemblies (used for the #5 and 6) have been designed at the cancellation of the project. These miter bends are mounted vertically one on top of the other with a spacing of 150mm, see figure 11. The assembly holds the miter bends in a sandwich structure. The sandwich is mounted on rails which can be displaced vertically and in the north south direction by ±20mm. The overall support is bolted to the barrier wall in J1T.

The second type of support (used for miter bends #2,3,4) is used when the miter bends are spaced broadly both vertically and horizontally. In this case the miter bends will be mounted in a large frame (~1.0m x 0.5m x 0.5m). The whole frame would be adjustable by ±20mm in three directions. This design would be different for each of the three miter bend positions, a preliminary design was not made before the cancellation of the project.

8.1.2 Wave-guide supports

The long horizontal runs (exceeding 6m in length) of the wave-guide line will need to be supported periodically over distances of 4 to 6m. The supports are designed based on experience gained in mounting the 63.5mm wave-guide line at CRPP. A small cradle is used to support the wave-guides vertically. All six to eight wave-guide lines will be supported at the same location. A typical support used along the wall in J1T is shown in figure 16. The position of the whole structure is adjustable vertically and horizontally. Each craddle can slide in a horizontal plane perpendicular to the axis of the wave-guide.

The wave-guide is self aligning, constrining the craddle would force a misalignment and increase the mode conversion. The only mis-alignment possible will be in the vertical plane, due to height misalignment. The supports in J1D would have followed a similar design using two long horizontal bars with 3 or 4 craddles mounted on each bar. This structure would have been supported from the Diagnostic platform structure. (in J1D) to attach the support structure. The overall precision with such supports is ~±0.5mm.

A conceptual design of these supports has been performed at CRPP. The machining of these supports were envisioned to be performed by CRPP's machine shop. The Operator would be responsible to mount a plate on the wall (for J1T) or steel work

8.1.3 Trestle bridge

A special support structure is required for the wave-guide between the East wall of J1T up to the entrance to the tokamak. When the remote handling unit is installed during openings to the torus, the wave-guides and their support structures from the east wall to the launcher must be removed. Dismantling the wave-guide piece by piece is feasible but time consuming, especially when re-mounting the lines. To simplify the dismounting and re-mounting of the wave-guide will be supported by a trestle bridge spanning the distance from the East wall to the launcher port, see figure 12. When the wave-guide is to be removed, the trestle bridge and wave-guide is removed in one piece. Each line is disconnected before the power monitor and before the CVD window unit. The trestle bridge will be supported from the east wall and with cables supported from the hooks at the torus for the remote handling unit. Hooks will also be mounted on the trestle bridge so that the structure can be lifted out of place with the overhead crane. The wave-guide will be mounted directly on to the trestle bridge. The support system will be similar to the wave-guide support structure described above and will allow for horizontal and vertical adjustment of the wave-guide for alignment.

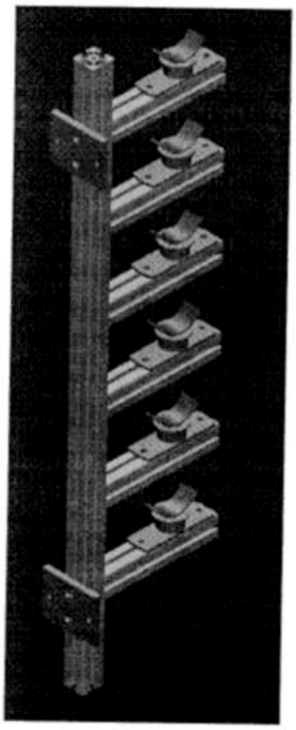


Figure 16 Cradle system used to support the waveguides. The whole assembly can be aligned horizontally and vertically.

The wave-guides will be supported at the switch and about 3m from the launcher. In case of launcher failure the wave-guide lines will need to be displaced slightly to the south to compenstate for the tilting of the wave-guide as described in section 3.6. A 25mm shift horizontally is needed for adjusting the line in case of a launcher failure, this flexibility will be included in the design of the support structures on the trestle bridge.

Wave-guide switches will be included in the wave-guide run on the trestle bridge. These switches allow the deviation of a beam from the tokamak to the load via a return path on the neighboring gyrotron's wave-guide line. The switch will be mounted directly on the trestle bridge with the alignment adjustable to accommodate the 25mm shift described above.

The trestle bridge will be manufactured by CRPP and then shipped to Culham, England. It will be made in two parts which can be bolted together on-site.

8.1.4 CVD window housing unit supports

The CVD window unit is the most fragile piece of wave-guide in the entire line and unfortunately it must be placed in the region which encounters the greaest stress in the wave-guide line, next to the torus. The wave-guide near the torus will bend slightly to accommodate the torus displacements due to thermal cycles and disruptions (see following section). Stresses of the order of 100MPa are expected to occur in the last section of wave-guide. To avoid these stress from being induced on the CVD diamond window, the window unit will be mounted directly to the torus flange and will move with the torus. The related forces then will be transmitted to the wave-guide and not the window unit.

The frame which supports the window housing unit will also support the gate valve, MB #9 and the section of wave-guide between MB's #8 and 9. The whole assembly of these elements and the frame can be mounted and dismounted together. The design of the frame will be made by the FOM team, since the launcher flange design is under their responsibility. The exact design requires the dimensions of the CVD window housing unit which was not defined at the time of this report. Note the responsibility of the CVD window housing unit lies with FZK.

8.1.5 Torus Displacements

The torus will move due to heating cycles and plasma disruptions while the wave-guide will be fixed in space. To accomodate the torus displacement the wave-guide must be flexible and bend with the torus movement without undergoing plastic deformation. The torus is nominally heated to 320°C which corresponds to a radial displacement in the region of the launcher port of ~18mm. During a disruption the largest displacement of the torus is 16mm radially and 9.5mm toroidally (6MA 4T). Since JET operations are limited to 5MA, the maximum torus displacement is only 13.5mm radially and 8mm toroidally, see figure 6. The displacement is a concern for ECRH transmission lines only due to potential damage of the wave-guides due to bending. Since the beam will be shut off during disruptions, there will be no concern for mode conversion losses arising from wave-guide bends except for displacements of the torus over the small range of operating temperature (200 - 320°C), which will be discussed at the end of this section.

The wave-guide will be mounted and aligned when the torus is heated which limits the relative displacement to ±16mm radially and 8mm toroidally. Two sections of wave-guide are used to compensate for the radial and toroidal displaments. The section of wave-guide between the 8th and 9th miter bend compensates for the radially displacement. The stress induced by a displacement of one end of the wave-guide a distance 'Δ' is given by[15]:

$$Stress = \frac{3E\Delta\phi}{2L^2}$$

where E is the modulus of elasticity of the wave-guide (69Gpa), ϕ is the wave-guide outer radius and L is the length of the wave-guide section. The Yield strength of 6061-T6 Aluminum is >260MPa, if L is 1.2m in length the resulting stresses induced in the wave-guide for 16mm displacement corresponds to 86MPa of one third of the Yield strength.

MB #8 is usupported, the next support is located >1m preceeding this miter bend. The toroidal displacement of the torus during disruption is taken up in this 1m section of wave-guide. The stresses induced in the 1m section for 8mm toroidal displacement is 62Gpa, well below the Yield strength.

During a disruption there will be ~7G forces submittted to the wave-guide which translates to a force of 0.6MPa, well below the limit for plaastic deformation of 260MPa.

8.2 Alignment and measuring procedures

The procedure for aligning and mounting the wave-guide will be similar to that performed in installing the transmission line at CRPP. Using a theodilite, the positions of all the miter bends will be located in space and the distances relative to each bend measured for obtaining relatively accurate lengths (±5mm) between each bend. These measurements will be sufficient for ordering the needed wave-guide lengths. Upon mounting the transmission line one wave-guide piece will be machined on site to compensate for the above inaccuracies.

Once the pieces are received the miter bends will be mounted first starting from the gyrotron and proceeding toward the launcher. A laser alignment device is used to align each miter bend, the laser fits into a holder which can slide into the input or output of the wave-guide on either arm of the miter bend. The laser beam is coaxial with the axis of the input/output arm of the miter bend and propagates up to the next miter bend. A mirror is placed on the input of the following miter bend, once the beam is centered on the input of the following bend and reflects back on itself, then that section of line is aligned. Supports between the two miter bends can then be positioned relative to the laser beam. A similar procedure is followed for each miter bend. The supports for the miter bends and wave guides will be designed such that the other five wave guide lines will be aligned relative to the first line. Note the coupling system used to join two pieces of wave-guide elements are designed to 'self-aligning'.

8.3 Vacuum characteristics

The transmission line will be pumped via two pumping stations: one on the MOU in J1D and the other by a pumpout Tee in J1T near the barrier. A dry vac turbo pump with a pumping speed of 150liter/s is planned to be used on both pumping stations. The dry-vac is fairly compact, low maintenance and has a roughing pump included.

All wave-guide elements will be cleaned ultrasonically with a degreasing agent and detergent after machining proceeded by a final ultrasonic cleaning with cold deionized water and rinsed with alcohol. Afterwards the wave-guides will be packed in a dry nitrogen enviornment and then enclosed in nitrogen filled plastic bags sealed for shipping. Upon arrival the elements are ready for installation, and pumping without additional cleaning or baking.

8.4 Cooling systems

Since the transmission line will be carrying high power levels some elements will require active cooling. These elements include: miter bends, gatevalves, and CVD window housing unit. The wave-guides and other elements absorb some power as well but at low levels such that passive cooling via conduction to the surrounding air is sufficient. This section describes briefly what cooling systems are required.

8.4.1 Wave-guide

The wave-guides 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. The rise in temperature of each line is calculated assuming all of the lower and higher order modes are absorbed in the wave-guide and that the lines are cooled by free convection to air [15]:

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

Where ΔT is the temperature rise, Q' is the average heat flux per meter of wave-guide, A' is the surface area of one meter of wave-guide and h is the heat transfer which averages between 5 to 25watts/(m^2 K). The maximum absorbed power in the line includes the ohmic attneuation (0.83%), higher order modes coupling into the wave-guide (3.6%), higher order modes converted in the miter bends (1.88%) and mode conversion due to sagging and misalignment of the wave-guides (0.1% for a total of 64.1kW with 1MW from the gyrotron. The resulting steady state temperature rise in a 72m long line and operating at a 1% duty cycle is less than 4C assuming the lowest heat transfer. This implies passive cooling is sufficient for the transmission line. Note application of these wave guide on ITER would require active cooling since the gyrotrons will be CW, otherwise tempratures of nearly 400C would be obtained.

8.4.2 Other elements

The miter bends, switch, gate valves, CVD window-housing unit will all require cooling systems. The exact parameters will be specified by the manufacture to insure ample cooling of 2.0MW CW operation. The torus gatevalve and CVD window-housing unit will require a special cooling circuit, all cooling circuits on the torus have to be evacuated quickly in case a water leak is detected in the torus. The Operator will be responsible for this cooling circuit.

9 CONCLUSION

This report covers the design of the ECH evacuated waveguide transmission line that was planned for the JET-EP ECH system. The program was cancelled early in 2002, this report represents roughly the status of the design as it stood at that time. Although the report was written several months later it includes some of the details that were yet to be documented for the planned transmission line. A sufficient amount of details have been investigated to insure that a total of 8 evacuated 63.5mm wave-guide lines could have been installed for the JET-EP ECRH system. Had the project continued the details and volume of this report would have been significantly larger.