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ABSTRACT.
Quasi-Optical (QO) and Evacuated WaveGuide (EWG) Transmission Lines (TL) have been analyzed as possible solutions to transfer the power from the gyrotrons to the launcher. The EWG solution has been chosen as the reference TL solution due to the achieved space saving, its flexibility and its ITER relevance. The proposed EWG routing is compatible with the use of standard components, a small number of mitre bends and <5% of expected attenuation. Concerning the vacuum window, the only material currently available giving the power/pulse length combination is based on the use of disks in synthetic diamond (CVD). This choice gives the opportunity to adopt the window design proposed for the ITER project. A technical solution exploiting two separate single disk windows rather than a double window has been analyzed in order to fulfill safety requirements and to take into account problems arising in transmitting high power.

1. INTRODUCTION

In 2009 a feasibility study to evaluate an ECRH system on the JET tokamak has been conducted [1]. A specific comparison between different transmission line concepts has been considered even without the detailed layout of the system. As input data for this study we have considered a tritium compatible system, composed of 12 gyrotrons injecting 10MW of power for 20s.

2. CONCEPT OPTIONS

An analysis has been conducted to choose the appropriate solution to transmit the power from the gyrotrons to the launcher. Two concepts can be considered: a Quasi Optical (QO) TL, based on the use of several mirrors that transmit the TEM_{00} mode in air and an Evacuated WaveGuide (EWG) that transmit the low loss HE_{11} mode. While in several existing ECRH systems the TL is based on the EWG solution (TCV, TS, DIII-D, JT-60, LHD), only few of them use a QO solution (TJ-II, W7-X).

2.1. QUASI OPTICAL SOLUTION

As a reference solution for QO TL, no real experience exists at multi-megawatt level and for long pulse length, except for the tests of the W7-X system. The W7-X ECRH system can be profitably used to evaluate the requirements of a QO line and its applicability to the JET environment.

The space reserved in the W7-X plant for the transmission of 10 MW is a straight duct of 30m with a cross-section of 2.5×3m, directed towards the machine. Each TL is composed of 16 mirrors, 6 of which are multi-beam (5 beams on the same large surface). The overall transmission efficiency is ~86% [2]. The total length of TL is ~60m (depending on the gyrotron), while the distance between W7-X and the ECRH system building is ~30m. This solution, although well designed and well integrated in the W7-X system, is not viable in the case of JET, for a number of reasons:

- A great space is necessary in the JET Torus Hall and connected buildings and such a volume is not available.

– Periodical mirror cleaning is needed and can be in conflict with the access limitation in the Torus Hall
– A metallic shielding must be installed to absorb stray radiation and to maintain low humidity and low air temperature. At the same time it should permit the accessibility for the mirror cleaning.
– The Tritium segregation requires a double barrier to avoid any risk of contamination. A large diameter window would probably be required.
– This is not the ITER solution and cannot benefit from the ITER project development.

2.2. EVACUATED WAVEGUIDE SOLUTION

EWG consists of corrugated aluminium waveguide with an internal diameter of 63.5 mm, connecting the gyrotrons to the launcher with mechanical continuity. The 12 lines can be allocated in a bundle of 1×1.2m with 0.3m of inter-axis. The transmission efficiency is very high (~95% in TCV[3]). The advantages of using EWG are:

– The occupied volume is minimized.
– RF leakage is avoided, except for the DC break, where shielding is mandatory.
– Polarisers are located in the mitre bends, under vacuum, minimizing arc occurrence.
– Very low losses.
– No maintenance is needed after installation.
– Some conditioning pulses should be done at the beginning of the experimental campaign and just after opening the line or arc occurrence.
– The windows work with vacuum on both sides, which is the safest way.
– The EWG is the ITER solution.

The drawbacks of this solution are the rigidity with respect to torus displacements (thermal expansion and disruptions), the spurious mode conversion in repetitive alignment stands and the employment of auxiliary equipments.

2.3. PROPOSED SOLUTION

The Q.O. solution is not compatible with the JET environment because there is not enough space for the mirror routing and this is not relevant for ITER. EWG is the solution proposed. This solution allows the required space to be minimised, to have more flexibility in the routing, to be fully ITER relevant and therefore to exploit the development made for the ITER project being, at the same time, a test for ITER.

3. ROUTING

A separate study has been accomplished to choose the best positions of the gyrotron Hall in the JET plant and of the port in which the ECRH launcher can be installed [4]. Our study has therefore been based on the assumptions that the Gyrotron Hall is in a new building and the launcher is positioned in octant 2

Figure 1 shows the chosen solution: the gyrotrons will be located outside J1 north-west corner. The 12 WGs reach the vessel with only 6 mitre bends, crossing the Torus Hall wall via 12 small drilling holes.

4. TL COMPONENTS

A list of necessary components has been defined on the basis of the experience on similar systems.

- Corrugated waveguide (63.5mm i.d., $HE_{1,1}$ low loss mode): aluminium + INCONEL section connected to the launcher.
- 90^o Mitre bends, with plane mirrors; They are responsible for most of the losses, mainly due to diffraction and mode conversion.
- Beam Switch to direct the power into the load. It can be integrated in the Matching Optics Unit to simplify the layout and the distribution of components.
- Polariser: 2 Mitre Bends equipped with rotating corrugated surfaces (depth $\lambda/4$ and $\lambda/8$) remotely controlled in real time.
- Power monitor: a single Mitre Bend with detectors in both directions. Located as close as possible to the launcher.
- Sliding joints (bellows): to compensate length variation due to mechanical stress.
- DC break at the Torus Hall entrance.
- Gate valve: one before vessel, one after gyrotron+load
- Pumping unit: two groups to evacuate waveguides to 10^{-5} mBar through Pumping Tees.
- Load: 1MW/20s (cw equivalent) for every gyrotron.

The principal components exist and are routinely produced and tested at MW level.

Table 1 shows the quantity of each components for a single ECRH line, with an estimation of losses and the required cooling.

5. VACUUM WINDOW

Considering pulse length (20s) and transmitted power (1MW) the only choice is a synthetic diamond window. A good opportunity is to use the ITER design as a reference, with substantial synergy with ITER and possible support by F4E (design and procurement). In the previous JET-EP project [5] a double window based on the use of two diamond disks with a very small inter-space was proposed. This solution has been abandoned because it doesn't resolve the problem about how to detect the failure of one disk and moreover it is not ITER relevant. The actual ITER project presents one single disk CVD diamond window, with 1.11mm of thickness, 75mm of diameter [6] and without arc detector looking at the window surface. The segregation of tritium requires the presence of a double barrier. In this project the use of two separate ITER windows has been considered, one positioned close to the launcher and the other one at the entrance of Torus Hall (Figure 2). This arrangement appears safer because it reduces the risk of damaging both windows in one incident.

A technical point to be solved is how to detect a failure of one of the windows. The recommended standard JET solution used in similar diagnostic lines is reducing as much as possible the volume between the barriers and installing a real time leak test, filling the inter-space with a known gas such as Neon at 0.5 Bar and monitoring the presence of Ne in the vessel and in the rest of the EWG. However 0.5 Bar is not compatible with high power operation of the EWG (required 10^{-5} Bar), since the risk of arcing would significantly increase.

A different strategy proposed is looking for Tritium and/or He in real time between the windows during the operation and making an automatic Ne leak test by filling the inter-space at 0.5 Bar after the end of operation each day. This point requires further investigation to find an acceptable solution.

CONCLUSIONS

The EWG is the selected TL solution since the QO option is not ITER relevant and seems impossible for JET. The suggested routing is fully compatible with an EWG, allowing full use and hence testing of ITER components. Two routing options have been proposed and analyzed: In the best solution the number of MB is reduced to 6, allowing low overall losses (<5%). Concerning the vacuum window, a good opportunity is to use two separate ITER CVD windows per line. As the standard JET procedure for detecting damaged windows is not compatible with high power TL operation an alternative strategy is proposed.

ACKNOWLEDGMENTS

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Components	Quantity	Losses (%)	Cooling (l/min)
WG63	70m	0.23	–
Mitre Bend (required in the Torus Hall)	3	1.5	5
Power Monitor (=1 MB with detectors)	1	0.5	7
Polarizer (=2 MBs with movable mirrors)	1	1.4	20
Bellows	2	0.006	–
DC break (at the entrance of Torus Hall)	1	0.002	–
Gate valve (in the vicinity of windows)	2	0.002	–
Pumping T	3	0.003	–
Beam Switch	1	0.5	5
Load (able to sustain 1MW@20s)	1		360
	TOTAL	**4.13**	**407**

Table 1: Losses and required cooling. The total number of 90º bends is 6.

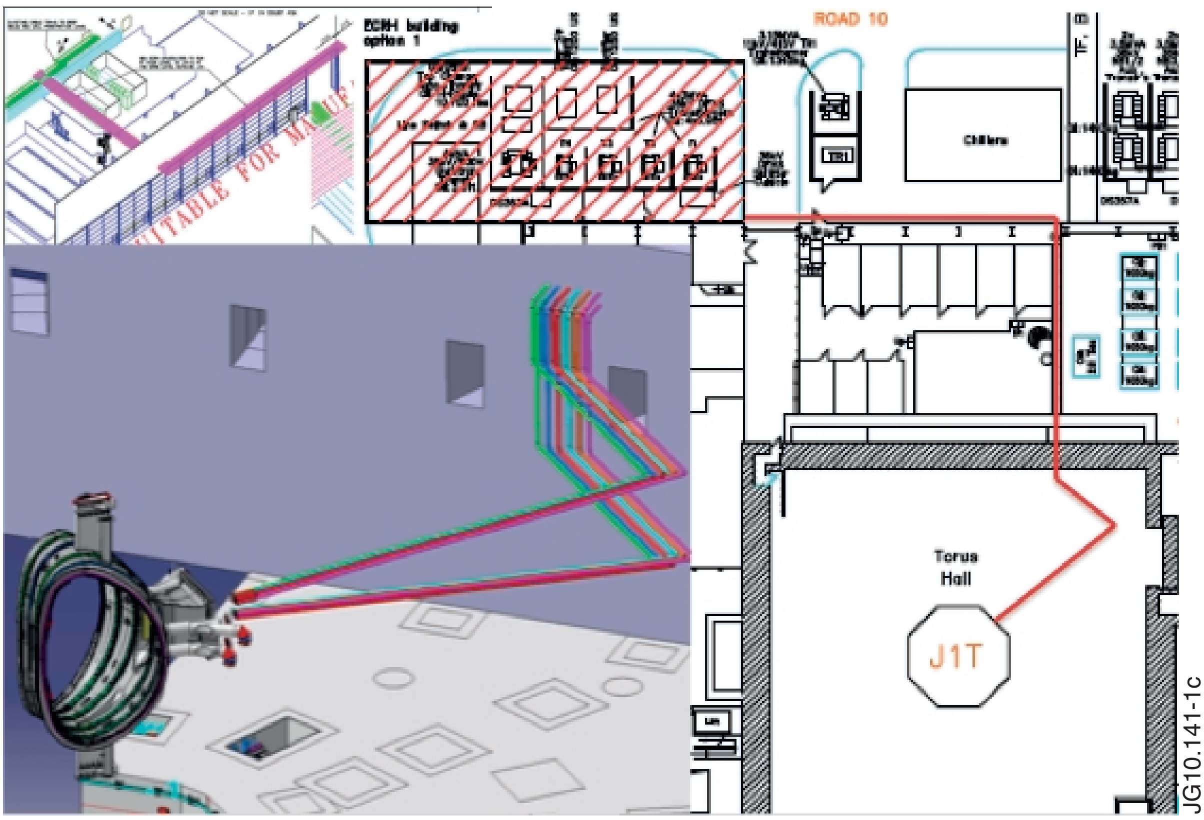

Figure 1. (Right) The suggested gyrotron building (the shadowed rectangle) and the approximate Transmission Line routing (red line). (Left): the route outside and through the J1H building (up) and the routing in the Torus Hall (down).

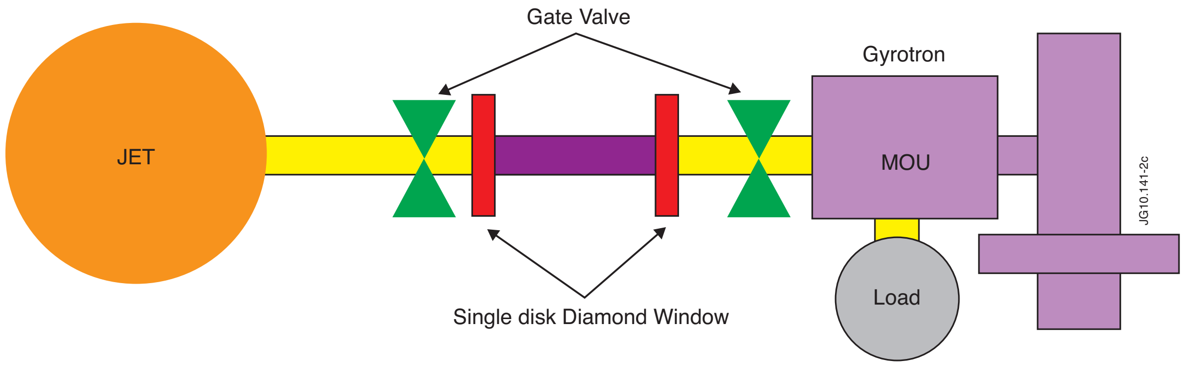

Figure 2. Proposed single line layout