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This document highlights several aspects associated with the ITER ECH system that should be improved in order to render the system more reliable, remove unnecessary components and reduce procurement costs. Particular attention is given to the interface issues associated with the transmission line and either the gyrotrons or launchers. The contents of this document was the basis of discussions between EFDA (the upper launcher group) and ITER-US during the summer of 2006. Several of these issues identified in this document were then used by those parties to formulate Issue Cards for the ITER ECH system at the end of 2006.

1 Introduction

The overall ECH system is shown in the following figure, which is based on the design as it stood in ~2000. The system is divided into 4 sub systems: power supplies, gyrotrons, transmission lines and launchers, as shown in figure 1.1.

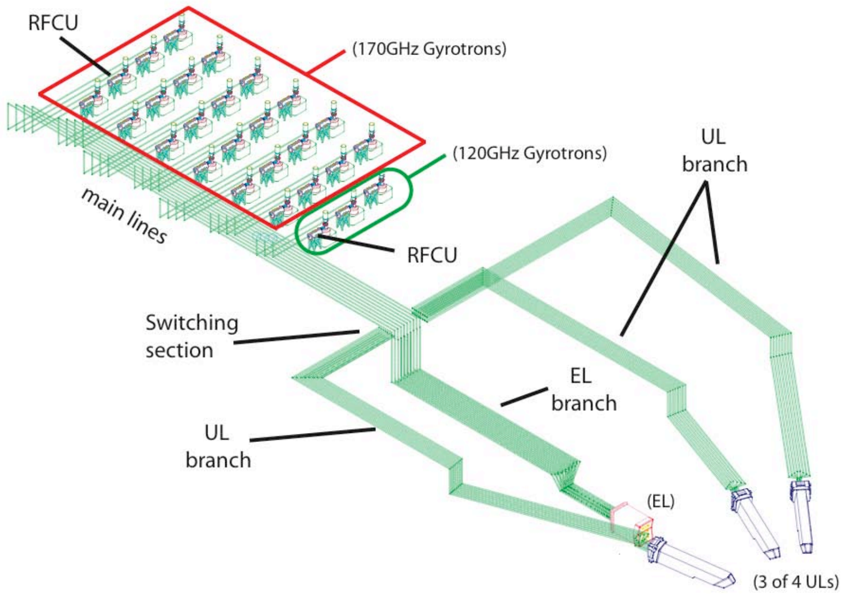

Figure 1.1 Drawing of the ITER ECH system, note that the forth port plug and associated waveguide line is not shown.

The present ITER ECH system is divided into 4 procurement packages as follows:

1) P1A=equatorial launcher
2) P1B=upper launcher
3) P2=Transmission lines
4) P3=RF sources and control

The packages P1A, P1B and P2 are to be procured by a single ITER partner, while the package P3 is subdivided into 6 sub-packages, see Table 1.1, which represents EU's understanding of the procurement plan.

Table 1.1 The EU's understanding of the ITER procurement packages.

Sub system	Procurement package	ITER Partner
Power supplies	H&CD PS	EU
	Start-up PS	IN
Gyrotrons[1]	8MW @ 170GHz	EU
	8MW @ 170GHz	JA
	8MW @ 170GHz	RF
	3MW @ 120GHz	IN
Transmission line	24 HE_{11} evacuated lines	US
Launchers[2]	1 Equatorial Launcher	JA
	3 Upper Launchers	EU

1) The procurement package specifies that 31% is supplied by EU, JA and RF with 8% from IN.
2) Although the PP for the upper launcher (P1B) mentions 4 upper ports, only three complete upper launchers to be installed in the torus are specified, while there will need to be four.

2 System requirements

2.1 Present ECH physics functionality

The EC physics objectives according to the present PID (Plant Integration Document) includes:

- Access H mode and heat plasma to Q>10
- Provide steady state current drive capability for DT, D, H and He plasmas
- Drive current
- Assist plasma control, and in particular provide stabilisation for neo-classical tearing modes (NTMs)
- Conduct wall conditioning during the inter-pulse and machine conditioning phase
- Assist the poloidal field system in establishing breakdown and current initiation

The deposition requirements for these applications are portrayed in figure 2.1.

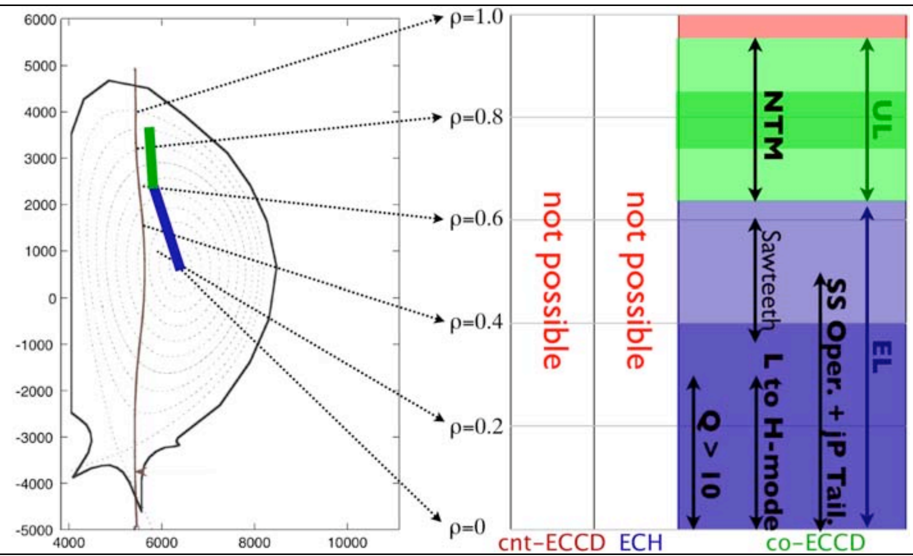

Figure 2.1 The present access requirements for the upper launcher (green zone) and equatorial launcher (blue zone) and the corresponding access requirements of the ECH&CD applications based on the PID.

In principle all desired applications can be achieved using the two launcher system with the access zone partitioned such that the equatorial launcher (EL) is used for applications from the plasma centre out to ρ_ψ~0.65 and the upper launcher for applications from ρ_ψ~0.65 outward.

2.2 Limitations with the present system

There are inadequacies in the present EC system. First of all the EL is required to cover all of the EC applications except for the NTM stabilisation, which implies a steering range twice that of the upper launcher (UL). The larger steering range implies a larger opening in the first wall, which is critical for the EL because of the neutron load. The EL is also supposed to be used for applications requiring both large driven current (used for current profile control, SS operation, etc.) and applications requiring narrow deposition profiles (for example sawteeth control), which is not feasible with a launcher having one steering degree of freedom.

In addition, the steering range of the EL from 20º≤ β ≤45º results in less than full absorption when the beams are steered beyond 40º for the reference scenarios 2, 3a and 5 as shown in figure 2.2. Other scenarios have yet to be evaluated~~.~~

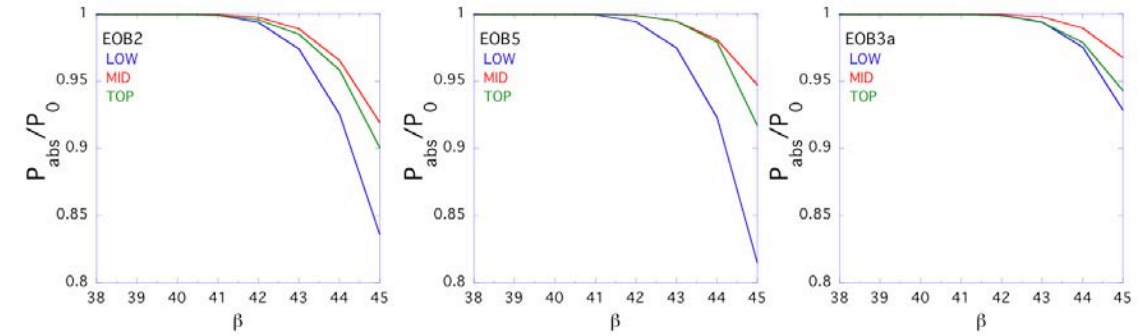

Figure 2.2 Fraction of absorbed power versus the toroidal scanning angle of the equatorial launcher. Less than full absorption occurs for β>40º.

Note that less than full absorption implies some of the power will be transmitted and incident on either a blanket shield module, a neighbouring diagnostic port or another heating system. For example 100kW would be transmitted through the plasma if 99.5% of the injected power is absorbed in the plasma 0.5% transmitted power (100kW) is sufficient to result in damage to diagnostics, local breakdown and possibly welding.

For these reasons the EL should be limited to a steering range of β≤40º, although this limit is based only on the above three reference scenarios and all scenarios should be investigated at various plasma conditions.

The primary role of the UL is to stabilise the NTMs, however, the UL can be used for sawtooth control applications without sacrificing efficiency on the NTM stabilisation. The UL can access $0.4\leq\rho_\psi\leq0.93$ with narrow deposition profiles, adequate for sawteeth control, FIR, etc. Despite the poor location of the upper port (very high with a long path length to the resonance) the deposition width is relatively narrow, since the resonant surface is tangential to the flux surfaces in the region of ρ_ψ~0.4.

The UL (shown in figure 2.3) can be made to access further inward by increasing the rotation of the steering mirror, however, this will result in increased stress of the steering mechanism and reducing the expected number of rotations possible prior to the onset of fatigue. An alternative option is to spread out the deposition range of the two steering mirrors (upper-USM and lower-LSM) such that the USM aims more centrally and the LSM aims more toward the plasma edge. Full power can be provided in the overlap region and partial power in the two extreme deposition locations, more details are provided in the following section. Spreading the deposition range reduces the rotation of the steering mechanism thus prolonging the life of the system, while offering an increased physics performance, thus enhancing both the physics and engineering aspects of the system.

Having the UL cover the range from ρ_ψ~0.4 to ρ_ψ~0.94, would relax the steering requirements of the EL. The smaller steering range would reduce the opening in the BSM needed and thus decrease the radiation on the EL steering mechanism, prolonging its longevity. Note that the BSM opening in this proposal results in a reduced opening in the BSM despite the additional steering range, again enhancing both physics and engineering aspects.

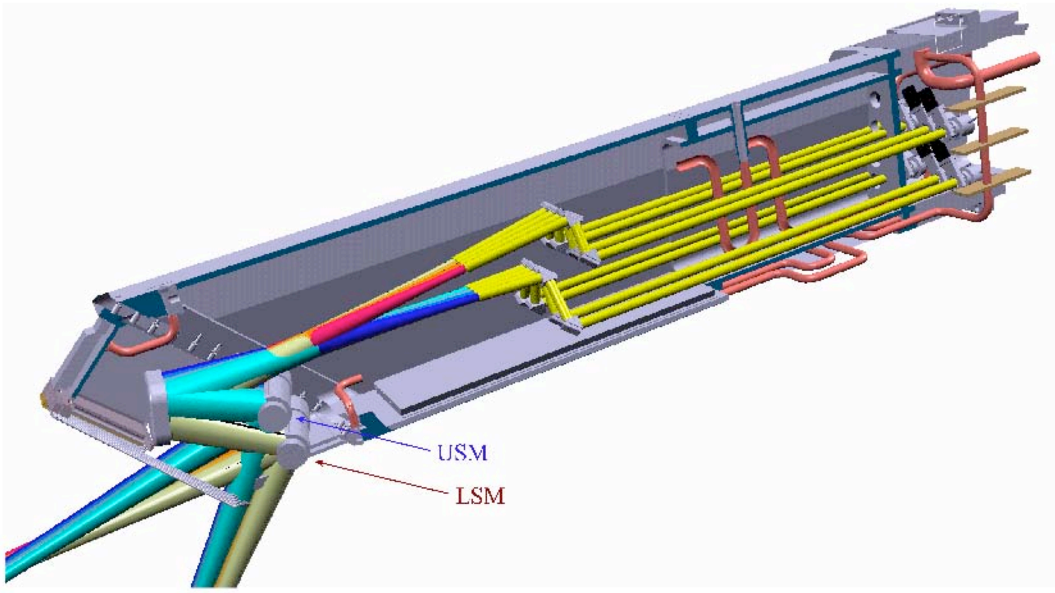

Figure 2.3 The mm-wave system of the upper launcher, which has a set of eight beams per port plug and two steering mirrors: upper (USM) and lower (LSM) steering mirrors.

2.3 *Enhanced physics (EP) capabilities*

The launchers can be modified to increase the physics performance and (in most cases) relax the engineering constraints. The UL and EL have different scanning planes (EL toroidal and UL poloidal) resulting in different current drive (CD) performance. The EL drives more total current and is useful for current profile tailoring applications, which typically require more central deposition ($0<\rho_\psi<0.5$). The UL is designed to have a peak current density profile (narrow deposition) useful for controlling NTMs and sawteeth, which require more off axis deposition ($0.4<\rho_\psi<0.9$). The combination of good focusing and large steering range achievable with the present UL design allows to increase its range of applications, relieving the EL of its sawtooth control application as shown figure 2.4.

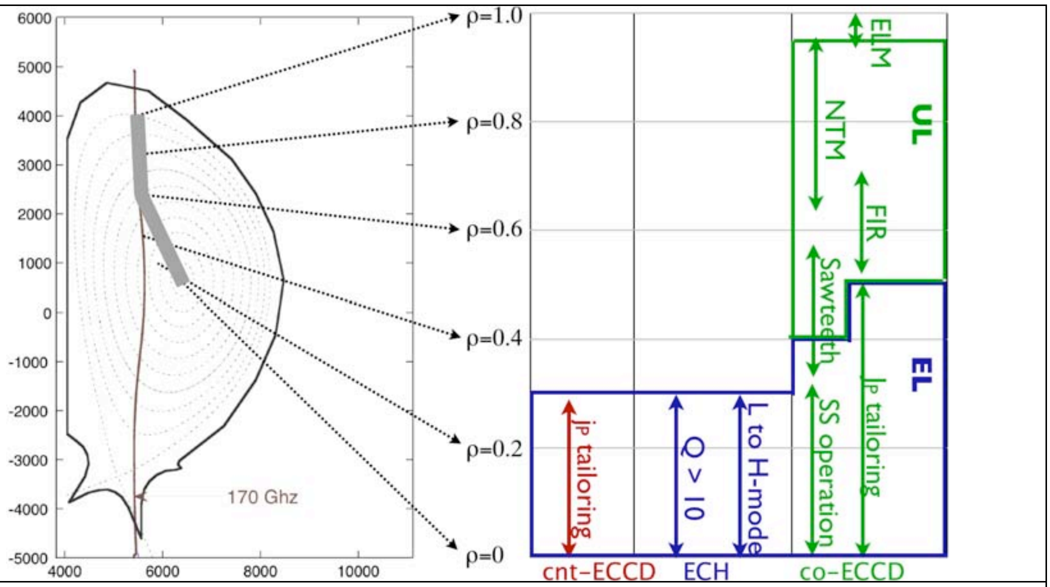

Figure 2.4 The proposed partitioning of launcher applications based on the launcher synergy study performed in collaboration between the EU and JAEA.

Note that the EL can be modified to provide counter ECCD useful for enhanced physics performance, which will be described later in this document.

2.4 *Design implications of EP on EC system*

2.4.1 *Upper Launcher*

The UL has 8 beams/ port as shown in figure 2.3. A poloidal view of the beams, focusing mirror, two steering mirrors (LSM and USM) and the relevant NTM flux surfaces is shown in figure 2.5a. The deposition range of the UL can be increased by spreading the deposition range of each steering mirror apart, with the LSM (red line of Figure 2.5) accessing further toward the plasma edge and the USM further inward (blue line). The black line represents the overlap region. Using this technique, the overall deposition range can be increased from $0.64<\rho_\psi<0.93$ to $0.4<\rho_\psi<0.93$ (as explained earlier in the above section).

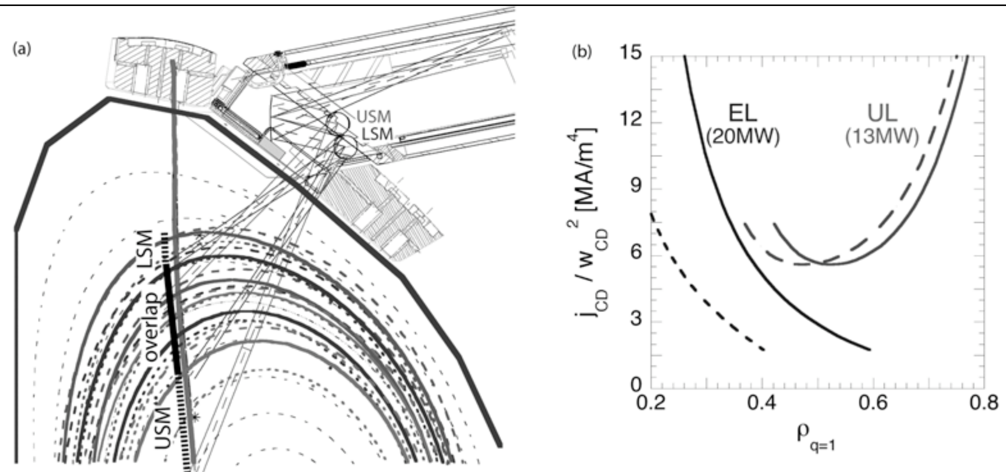

Figure 2.5 a) The deposition range is increased by spreading apart the scanning range of the USM and LSM. B) The 13MW in the UL is more effective in modifying the local shear (depends on I_{CD}/w_{CD}^1) on the q=1 implying that the UL should be used both control of the q=1 and q=3.2.

An additional switching system in the transmission line prior to the launchers will be needed to deviate the 24 beams to the 32 entries using a combination of 16 upper or 16 lower steering mirrors of the UL. This implies that only 13.3MW can be deposited in the innermost and outermost regions, which is adequate for NTM control and still exceeds the EL for sawtooth control (see the above figure). Note the solid (dashed) lines correspond to q=1 location for sawtooth de-stabilisation (stabilisation).

2.4.2 *Equatorial Launcher*

Reducing the steering range of the EL will reduce the size of the opening in the BSM, as shown in figure 2.6. The smaller opening will reduce the nuclear radiation on the steering mechanism.

a) b)

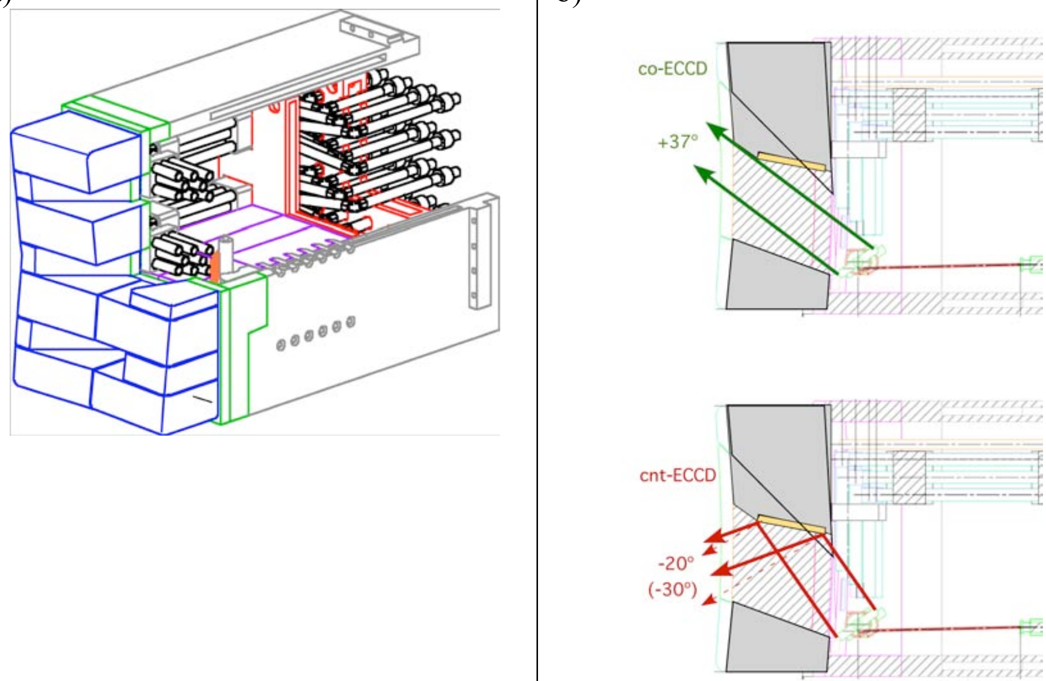

Figure 2.6 a) The equatorial launcher and b) a horizontal cut of the EL illustrating the smaller opening in the BSM related with the reduced steering range.

The black line in the vicinity of the BSM (see figure 2.6b) corresponds to the original opening of the BSM with a steering range of 20º to 45º. The gray area corresponds to the larger shield area (hashed area corresponds to the reduced opening) corresponding to a limited steering range of 20º to 37º (37º was used in this figure based on previous analysis, the figure will be revised once further analysis is made by JAEA).

It is possible to install a mirror on the sidewall of the BSM, such that the beams can be steered to this mirror and then reflected in the counter direction. This would result in driving negative current useful for either negating the co-ECCD (providing pure heating without peaking the plasma current profile) or current profile tailoring by increasing (or decreasing) the current hole in the centre and controlling q_0 and q_{min} in reverse shear profiles. Note that the EL will be a critical tool for current profile tailoring in all scenarios, for example to avoid hollow current profile with the addition of off-axis NB CD.

Reducing the opening will reduce the nuclear radiation on the steering mechanism. JAEA is also investigating replacing the last mitre bend with a free space mirror, which can be used to compress the beam assembly and further reduce the opening. The beam spot size on the mirrors would increase, reducing the peak power density such that the EL would be compatible with 2.0MW transmitted power.

2.4.3 <u>Transmission line</u>

The 4-port design of the UL has implications on the transmission line design. First of all, additional waveguide will be needed to connect the waveguide from the switching section to the 4th port, see figure 2.7. Note that the ULs will be located in ports 12, 13 15 and 16, and at present the 4th line is not included in the procurement package.

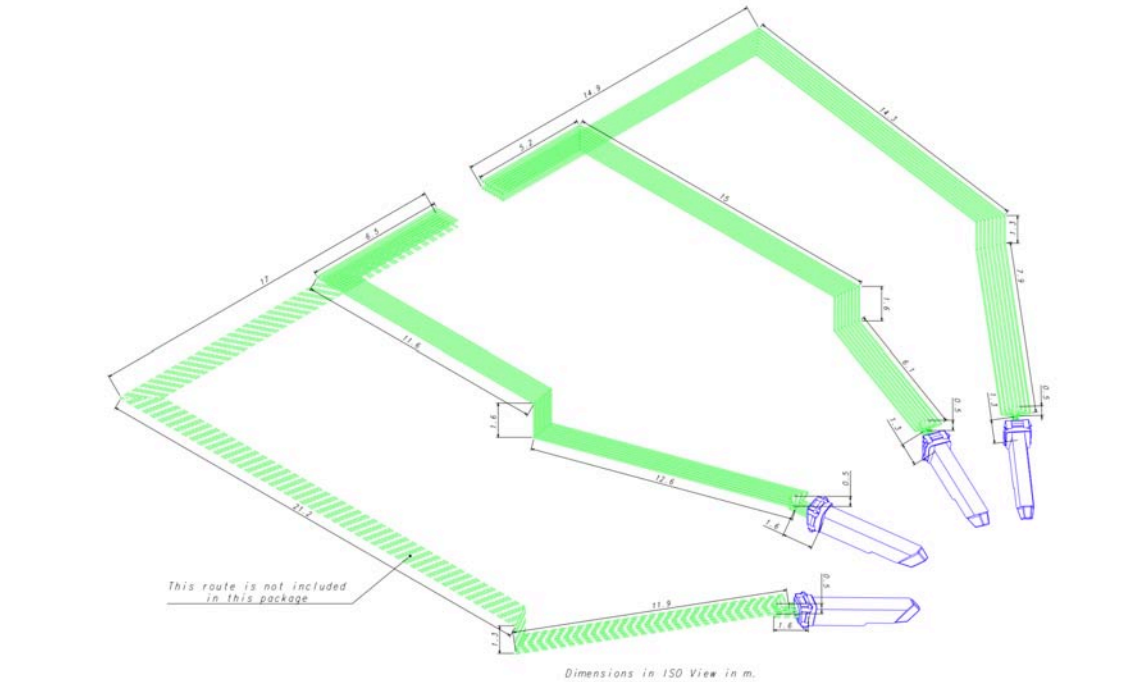

Figure 2.7 The transmission line sections leading from the switching network to the four upper port launchers.

Additional components will be needed for the transmission line prior to the UL to accommodate this design: ~8 in line switches in addition to the standard components needed prior to the launcher (mitre bends, ~pump out Tees, straight waveguide). The EU would be required to provide a fourth launcher.

The optimal location of the proposed switching system (between steering rows of the UL) is outside of the torus hall, as illustrated in figure 2.8. Placing the switch outside of the torus hall provides easy access for maintenance and modification of the gyrotron-transmission lines that are directed to a given launcher with such a switching system (only two of four launchers will need the additional switching system). This design would also keep the waveguide layout for all port plugs identical.

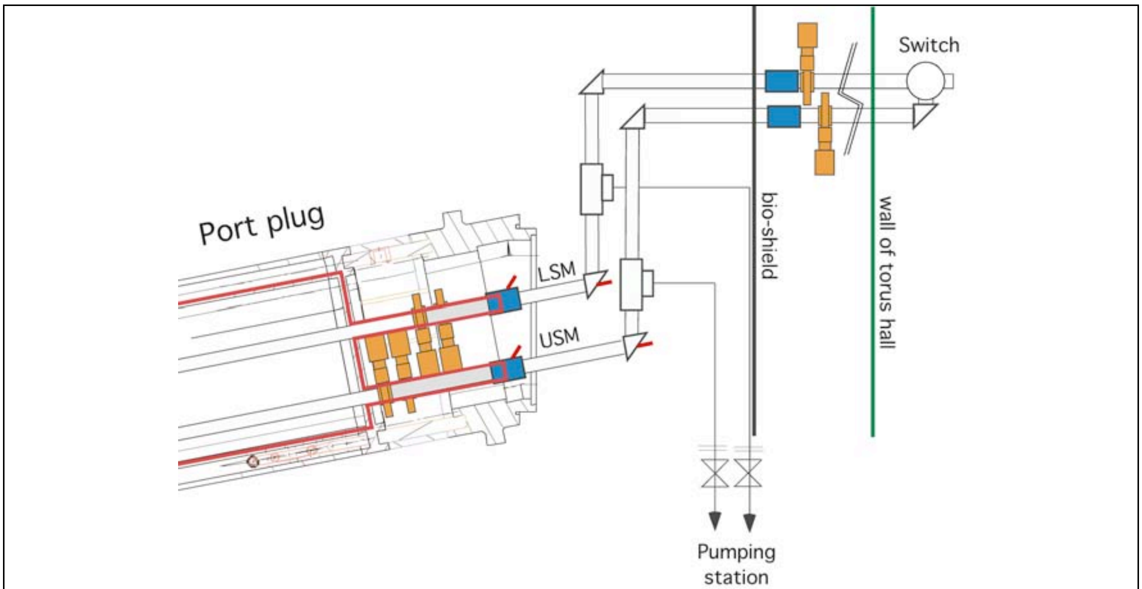

Figure 2.8 Illustration of the proposed switching system that would send the RF power to either the UL's upper or lower steering mirror. Note the optimum locations of the switching system would be outside of the torus hall for unlimited maintenance access.

2.5 2 MW Compatibility

The present gyrotron technology is providing sources with 1MW CW capabilities, for example the 140 GHz Thales® tube for the W7-X project. Gyrotron developers are now extending the output power toward 1.5MW and the EU is working on a co-axial gyrotron that is to deliver 2.0MW. Sources of >1 MW at CW will take time to develop. It is reasonable to expect the availability of such sources to occur within the next ten years prior to ITER's first plasma, or during 20 years operating period of ITER. Thus the transmission line should be rated for 2MW transmission from the start.

All components should be rated for 2MW CW operation, to be compatible with the EU gyrotron and possible upgrades in gyrotron development. The upper launcher is designed to be compatible with 2MW, peak power densities (~3.6 MW/m^2) occur on the mitre bends. A test mitre bend mirror is being purchased from GA (which is also providing the mitre bend housing) and tested in the JAEA 170 GHz, 1 MW test facility this year. The RF absorption is increased to simulate the conditions of the mitre bend in the port plug with 2MW incident power.

Modifications to the equatorial launcher are under consideration that would also accept 2 MW transmissions. One set of mitre bends can be replaced with free space mirrors, the mirror is placed ~1 m from the waveguide end so that the beam will expand to a relatively large diameter when incident on the mirror. The beam spot size is large enough such that the peak power density with 2MW will be less than that expected in the previous design with 1 MW transmission

The majority of the transmission line components are commercially available for 2.0MW operation. For instance, several of these components have been purchased from GA for the 170 GHz coaxial test facility at CRPP. Components such as straight waveguide, mitre bends, DC breaks, vacuum pumping sections and power monitors have been either delivered or guaranteed for 2MW operation. Critical components are the in-line switch and bellows. The highest absorption is highest on the switch takes place when the beam is incident on the mirror and with E-plane polarisation. The cooling circuits are not adequate in the present design; note that the tubing needs to be flexible to compensate for the mirror displacement. The bellows requires some redesigning to decrease the path from the flexible corrugated waveguide section to the nearest possible cooling clamp location, which is achievable by increasing the length of the GA bellows design and inserting a cooling clamp in the mid section of the bellows.

2.6 Optimum launcher position

It has been suggested that lowering of the port would improve the efficiency of the upper port launcher. Although this is true, the incurred costs and associated delays would very likely far out weigh the gain offered by such a modification.

The optimum frequency and injection location for the UL is determined by the geometrical launch conditions. The beam should be deposited over as few flux surfaces as possible in order to minimise the deposition profile width. This occurs when a narrow beam is tangential to the flux surfaces at the absorption location in the plasma, which can be achieved by changing the frequency (shifting the resonance layer to meet the tangential condition) or moving the port plug location for a fixed frequency. For the specific geometry of the UL, the ideal location would be in the BSM below the present location as illustrated in figure 2.9.

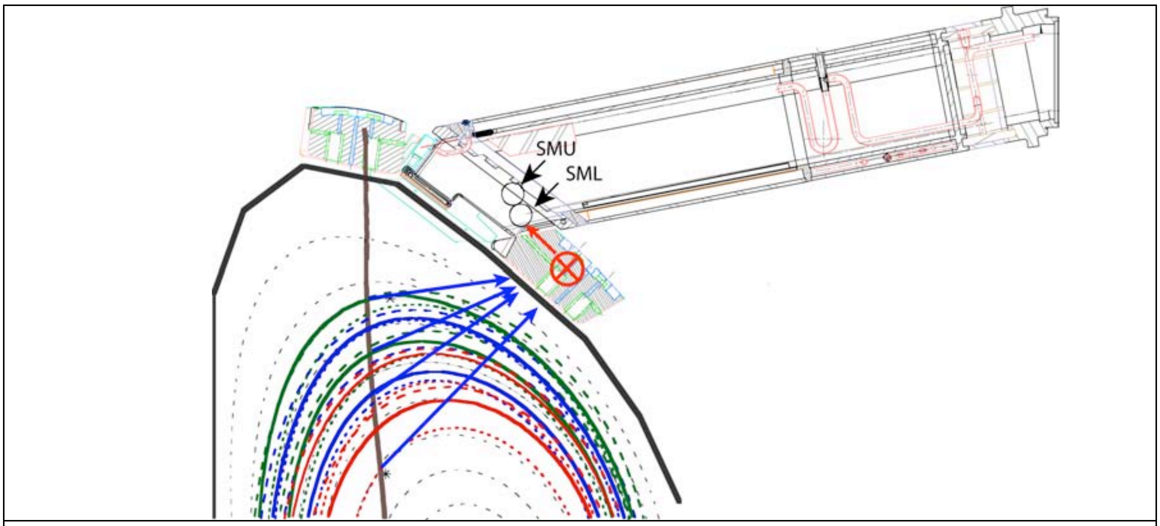

Figure 2.9 The optimum launch point is determined by the intersection of a set of lines tangential to the flux surfaces at the beam's deposition location, as shown by the red 'x'.

Moving the port plug down would improve the physics performance (by ~30%) of the any generic upper launcher. However, such a modification would require a significant amount of design work to the magnetics, cryomagnet, port plug design, vacuum vessel and building. The impact on schedule and costs has not been estimated in detail. The EU EC team is proceeding in the assumption that the port allocation/inclination are fixed.

2.7 *Optimum gyrotron frequency*

It has also been suggested that a change in gyrotron frequency would improve the overall performance of the EC system. This is true for the upper port when ITER is operating at nominal field, but it is incorrect when considering the EL or reduced field performance. Note that a single frequency is used for both UL and EL to reduce costs. Multi-frequency gyrotrons could increase the flexibility but the present technology is not adequate for application on the ITER EC system.

The optimum frequency for the UL would be toward higher frequencies in the range of 180 to 190GHz for the present launch position, point "A" of the figure 2.10. The resonance surface is shifted toward the high field side (HFS), the launching geometry results in the beam tangential to the magnetic flux surfaces at the absorption region

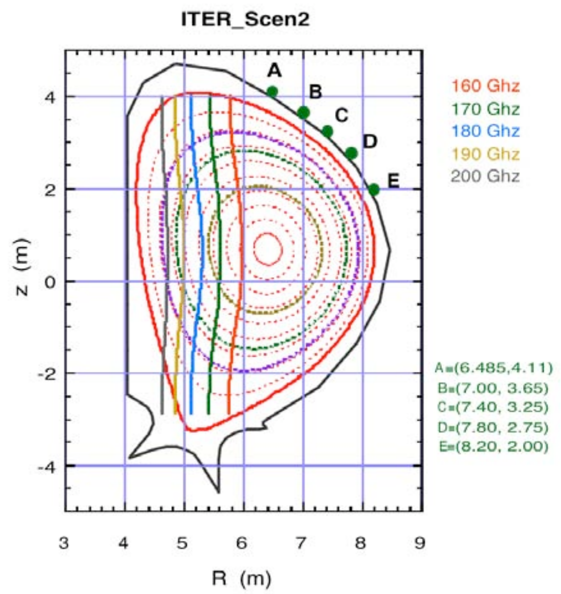

Figure 2.10 The resonance locations at different RF frequencies and launch points investigated for the optimum RF performance of the UL.

Shifting the frequency up would limit the central access obtained from the EL. The optimum frequency of 170GHz was chosen for the nominal field parameters of ITER and as a compromise between the two launchers. A lower frequency would have increased the operating range of the EL and UL launchers when operating ITER at lower field strengths.

Note that changing the frequency optimizes the orientation such that the beam is tangential to the flux surface at its absorption location (at nominal field strength). Therefore, the benefit of the frequency shift is equivalent to the shift of the port plug position. The benefits of both modifications cannot be additive.

3 Observations and possible improvements to the T-line

The present procurement package for the transmission line includes the subsystems described in table 3.1.

Table 3.1 The deliveries associated with the ITER ECH transmission line.

Del. #1	Main transmission line
Del. #2	Upper launcher transmission line
Del. #3	Hot cell transmission line
Del. #4	Transportable transmission line test set
Del. #5	Assembly tooling

3.1 Main transmission line

The main transmission line is comprised of all components from the gyrotron to the equatorial launcher. The components are listed in the following table. In some cases, the utility of some components are questionable, in which case a brief comment is given in table 3.2.

Table 3.2 The components to be procured in the first delivery of the transmission line.

Item	Description	Quantity	Comment

1	RF conditioning unit (170 GHz)	25	See 1
2	RF conditioning unit (120 GHz)	3	See 1
3	HE_{11} waveguide (Al)	1’900m	
4	HE_{11} waveguide (SS)	172m	See 2
5	Bellows for penetration of 2^{nd} closure plate (+4 spares)	28	See 3
6	Mitre bends (+4 pares)	100	See 4
7	Directional couplers (+4 spares)	55	See 5
8	DC break (+4 spares)	55	
9	Thermal Exp. section (+4 spares)	178	See 3
10	Rupture disk (+4 spares)	28	See 6
11	Vacuum pumping section (+4 spares)	28	See 7
12	Gate valve (+4 spares)	28	See 8
13	Waveguide switch	3	See 9
14	Waveguide support	432	
15	Support frame	38	
16	Assemblies & mounting for vacuum window	As Req.	See 10
17	Tools for RH and hot cell	As Req.	

1) GA has proposed that the RFCU is replaced with an MOU, mitre bend polarizers, in-line switch and short pulse load. This should reduce the total cost and improve the transmission efficiency. Both EU and JAEA recommend that the MOU is delivered with the gyrotron (as is traditionally done), other wise 4 different MOUs, for each gyrotron-cryomagnet type, would need to be procured by the US. If the MOU is delivered with the gyrotron than a certain mode purity would be required (or will need to be prescribed) to insure optimal coupling from the free space to waveguide modes. The short pulse load should be interchangeable with a long pulse load for acceptance testing and conditioning.

2) There is no need for SS HE_{11} waveguide in the transmission line procurement package. The SS was required for components that will see the torus vacuum and baking temperatures up to 240ºC, which is not the case for all transmission line waveguide components. Note that the SS waveguide is roughly a factor of 3 more in costs compared to Al.

3) The bellows (assumed to be for compensating torus displacements in the radial or vertical directions) and thermal expansion joints can easily be substituted by straight sections of waveguide, careful design of the support structure and aligning the waveguide under nominal operating conditions (avoiding losses associated with waveguide bending). Thermal variations could be compensated by the waveguide flexibility. Note that some in-line bellows are advisable, mainly in long straight sections of the waveguide.

4) This assumes 6 mitre bends per line (including 2 power monitors, item #7). It is advisable to increase the number to 7 per line so that 3 mitre bends (power monitor plus two polarizer mitre bends) can all be located on the gyrotron

mezzanine level. The majority of the mitre bends should have an arc detection system included in the mirror.

5) Only one directional coupler (or power monitor) is needed per line, the second (located near the launcher entrance) will not provide an accurate representation of the directed power since the signal will vary significantly due to a changes in the local electric field arising from a small percentage of lower order modes. The power at the entrance to the launcher can be calibrated either using the absorbed power in the diamond window or pre calibrating the power transmitted at the end of the line.

6) The rupture disks can be incorporated in the vacuum pumping section near the launcher; this will reduce cost and perform the same function.

7) The vacuum pumping sections should be located near 2/3 of the distance from the gyrotrons to the switching system. It may be more effective to place a vacuum pumping section on each branch line going to either the upper or equatorial launchers. Then each branch could be evacuated separately, required in case of diamond window failure in one branch. The vacuum pumping system near the launcher will require the possibility to leak a trace gas into the HE_{11} line for leak testing the diamond window or access for a mass spectrometer to search for such trace gas leaked in from the opposing side of the diamond window.

8) EFDA/CRPP is working with VAT to provide an ITER all metal gate valves; this activity could proceed in collaboration with the US. An alternative solution is to include an isolation valve in the in-line switch (standard GA design) where the power is diverted to either launcher. This isolates each branch and provides a secondary tritium barrier.

9) The switch should be similar to the switch described above with gate valves at the input arms (rather than output) so that the two waveguide sections leading to either the 170 GHz or 120 GHz gyrotrons can be isolated. Note that a vacuum pumping station is needed between the two switches of the three lines used for the two gyrotrons.

10) The vacuum window is a part of the launcher (or gyrotron) procurement package.

3.2 Upper launcher transmission line

The upper launcher transmission line is comprised of all components from the switching system to the upper launcher. The components are listed in the following table. In some cases, the utility of some components are questionable, in which case a brief comment is given in table 3.3.

Table 3.3 The components to be procured in the second delivery of the transmission line.

Item	Description	Quantity	Comment
1	HE_{11} waveguide (Al)	800m	See 1
2	HE_{11} waveguide (SS)	144m	See 2
3	Bellows for penetration of 2nd closure plate	24m	See 3
4	Mitre bends	96	See 4
5	Directional couplers	24	See 5

6	DC break	24	
7	Thermal Exp. section	120	See 3
8	Rupture disk	24	See 6
9	Vacuum pumping section	24	See 7
10	Gate valve	24	See 8
11	Waveguide cap including spare lines	32	See 9
12	Waveguide support	248	
13	Support frame	31	
14	Assemblies & mounting for vacuum window	As Req.	See 10
15	Auxiliary Equipment for R. H. and hot cell tooling	As Req.	

1) Approximately an additional 400m of waveguide will be needed for connecting the fourth launcher.

2) There is no need for SS HE_{11} waveguide in the transmission line procurement package. The SS was required for components that will see the torus vacuum and baking temperatures up to 240ºC, which is not the case for all transmission line waveguide components. Note that the SS waveguide is roughly factor of 3 more in costs compared to Al.

3) The bellows (assumed to be for compensating torus in the radial or vertical) and thermal expansion joints can easily be compensated by straight sections of waveguide, careful design of the support structure and aligning the waveguide under nominal operating conditions. Thermal variations could be compensated by the waveguide flexibility. Note that some in-line bellows are advisable, mainly in long straight sections of the waveguide for example between the gyrotron mezzanine to the torus hall. The bellows are not recommended in the port duct area or the launcher.

4) This assumes 4 additional mitre bends per line (including 1 power monitors, item #5). The majority of the mitre bends should have an arc detection system included in the mirror. 8 additional mitre bends will be needed for the switching system in the UL that deviates the RF power to either the upper or lower steering mirror

5) The directional coupler (power monitor) located near the launcher entrance will not provide an accurate representation of the directed power since the signal will vary significantly due to a changes in the local electric field arising from a small percentage of lower order modes. The power at the entrance to the launcher can be calibrated either using the absorbed power in the diamond window or pre calibrating the power transmission of the line. Therefore, this component should not be included in the transmission line.

6) The rupture disks can be incorporated in the vacuum pumping section near the launcher; this will reduce cost and perform the same function.

7) The vacuum pumping system near the launcher will require the possibility to leak a trace gas into the HE_{11} line to leak test the diamond window or access for

a mass spectrometer to search for such trace gas leaked in from the opposing side of the diamond window.

8) EFDA/CRPP is working with VAT to provide an ITER gate valve; this activity could proceed in collaboration with the US. An alternative solution is to include an isolation valve in the in-line switch (standard GA design) where the power is diverted to either launcher. This isolates each branch and provides a secondary tritium barrier.

9) The switch should have gate valves at the output of each branch (GA has a design with the switch and valves included together as one component). This would allow vacuum isolation of the transmission line branches to either launcher. Note that this component is the limiting factor for the transmission of 2.0MW operation.

10) The vacuum window is a part of the gyrotron procurement package.

3.3 Hot cell transmission line

High power measurements of the launcher in the hot cell are no longer expected to be a requirement (based on discussions between ITER-IT and EFDA). Therefore all components related to the high power transmission of the RF beam from a gyrotron to the hot cell should no longer be procured. These components are listed in table 3.4.

Table 3.4 The components to be procured in the third delivery of the transmission line.

Item	Description	Quantity	Comment
1	Transmission line from main assembly hall	2 lines	remove
2	Waveguide switch	2m	remove
3	HE_{11} waveguide (Al)	200m	remove
4	Mitre bends	20	remove
5	Thermal Exp. section	20	remove
6	Vacuum pumping section	2	remove
7	Directional coupler	2	remove
8	Waveguide support	50	remove
9	Support frame	25	remove
10	Control and monitoring	As Req.	remove

3.4 Test set transmission line

The concept of a portable test line is questionable. Each gyrotron should be installed directly into its designated cryomagnet. Each time a gyrotron is moved to a new cryomagnet it needs to be conditioned.

Portable facilities that allow measurement of output mode purity and beam direction could be used for optimising the MOU alignment. However, based on factory acceptance tests, this may not be necessary. The most critical function is to condition the gyrotron to long pulse operation and measure the power coupled to the transmission line. In this case only a few (four) long pulse loads are required in addition to the components already included in the main transmission line (assuming design proposed by GA using MOU, in-line switch and load). The four loads provide the possibility to condition/accept up to 4 gyrotrons at any given time or provide adequate spares.

Table 3.5 The components to be procured in the forth delivery of the transmission line.

Item	Description	Quantity	Comment
1	Dummy loads	4	See 1
2	k-spectrometers	4	See 2
3	Calorimetry sets	4	
4	Mechanical Assembly	1	See 3
5	Diagnostic station	1	See 3

1) The long pulse load must be capable of being installed in place of the short pulse load. Calorimetric measurements can be performed using the diamond window or power monitor mitre bend (cross calibrated with the short pulse calorimetric load).

2) There is no need for the k-spectrometers, mode purity can be determined either using an infrared camera or burn patterns in the transmission line. Note that the output beam from the gyrotron/MOU should be fully characterised during the factory acceptance tests. A reduced set of tests (such as burn pattern measurements and/or thermal camera measurements of burn pattern) can be performed on site to insure that no damage to the components occurred during transportation.

3) The number of assemblies/stations should be equal to the number of loads used for testing gyrotrons. Four systems should be adequate for accepting/conditioning/testing the H&CD gyrotrons.

3.5 *Gyrotron-waveguide layout*

The layout of the transmission line on the mezzanine and near the torus can be optimised to improve access and maintainability and/or reduce the number of components. For example, the present transmission line layout has the waveguide passing very close to the neighbouring gyrotron as shown in figure 3.1.

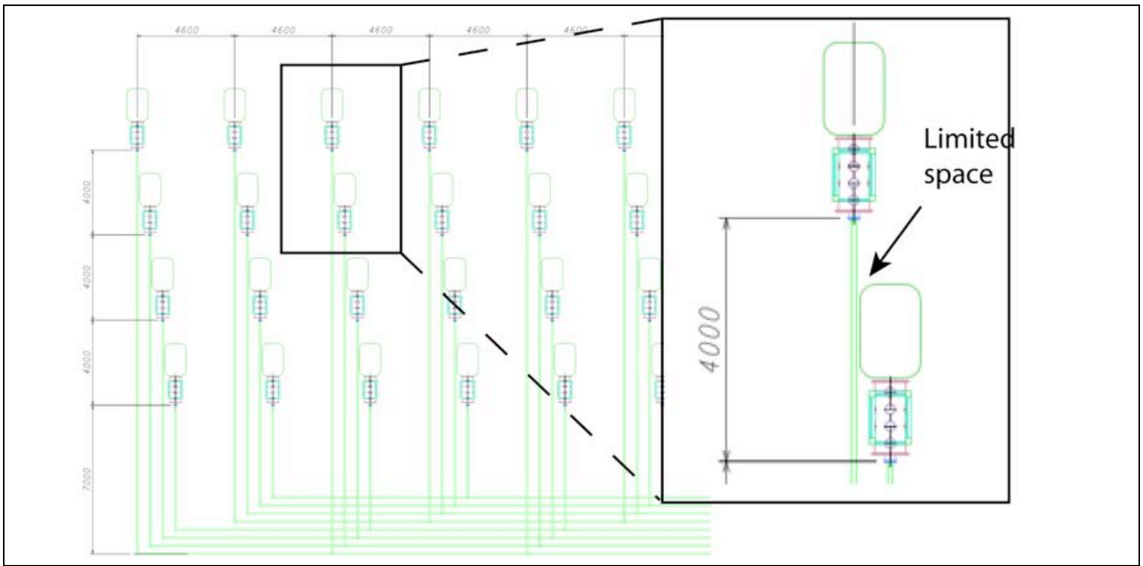

Figure 3.1 The present conceptual design of the transmission line has the waveguide passing very close to the neighbouring gyrotron, which would be very impractical for installation and maintenance of the gyrotrons.

The rectangular section representing the gyrotron and support stand is relatively small, with the waveguide passing very close to the assembly. This will hinder the installation and maintenance access around the gyrotron. An alternative layout is shown in figure 3.2 that avoids the waveguide components from being placed near the gyrotrons.

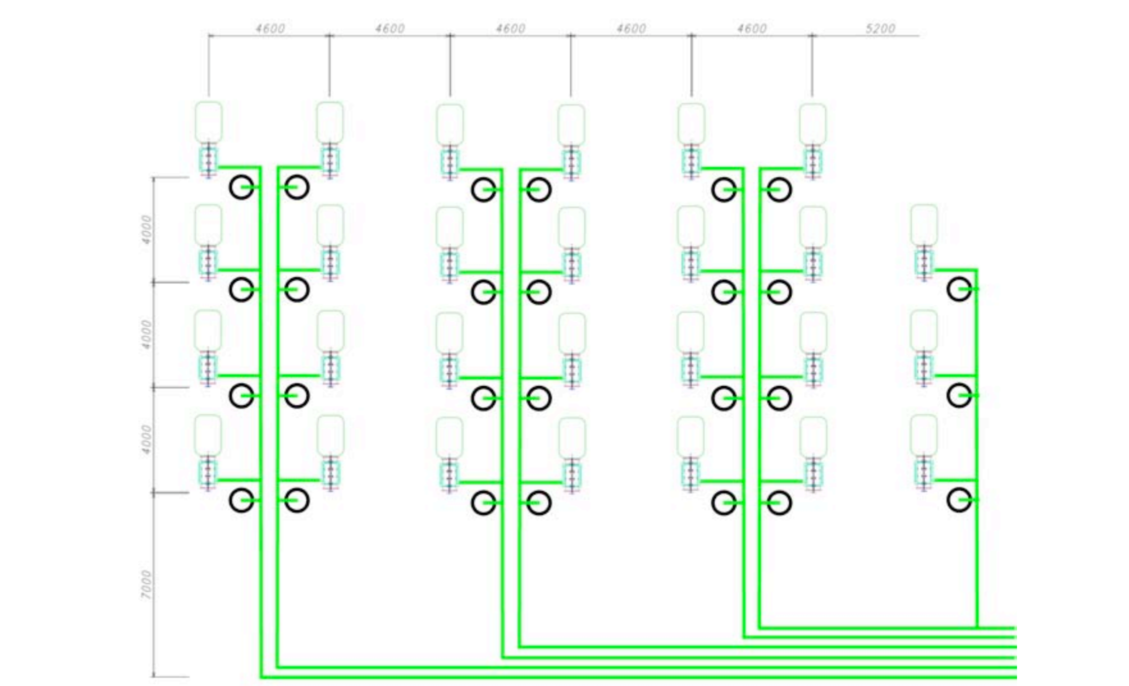

Figure 3.2 An alternative waveguide arrangement near the gyrotron that includes the option for inline switch-load assembly positioned after the power monitor mitre bend.

The waveguides from two pods are grouped together so that the support structures are reduced. There is adequate space near the gyrotron to place the in-line switch and load (black circle). Note that there should be three mitre bends (two polarizers and one power monitor) in the mezzanine area, which is consistent with this layout. There are two mitre bends with a vertical section after the MOU and prior to the in-line switch. One of the two first mitre bends should be a power monitor and the other a polarizer (power monitor should be placed prior to the switch-load for cross-calibration of the power measurements). The second polarizer is the next mitre bend in line where all the lines are grouped together.

3.6 Procurement boundary

The EU UL team has analysed the definition of the boundaries between the launcher and transmission line along with the transmission line and gyrotrons, with the aim of improving the EC operation. Note that a change in procurement boundaries requires negotiations between ITER and partners. The EU UL team takes the view that modifications in the costs should result in a redistribution of the credits for each partner and would not automatically increase or decrease a partners overall contribution to ITER.

The suggested modifications are motivated to:

1) Decouple the procurement interfaces from safety boundaries
2) Optimisation and simplification of interfaces between procurement packages (Note: functionally, these are not real interfaces, because they occur within one system)

3.6.1 *Boundaries based on Present Procurement Package*

The present boundary between the different subsystems of the EC system is illustrated in figure 3.3.

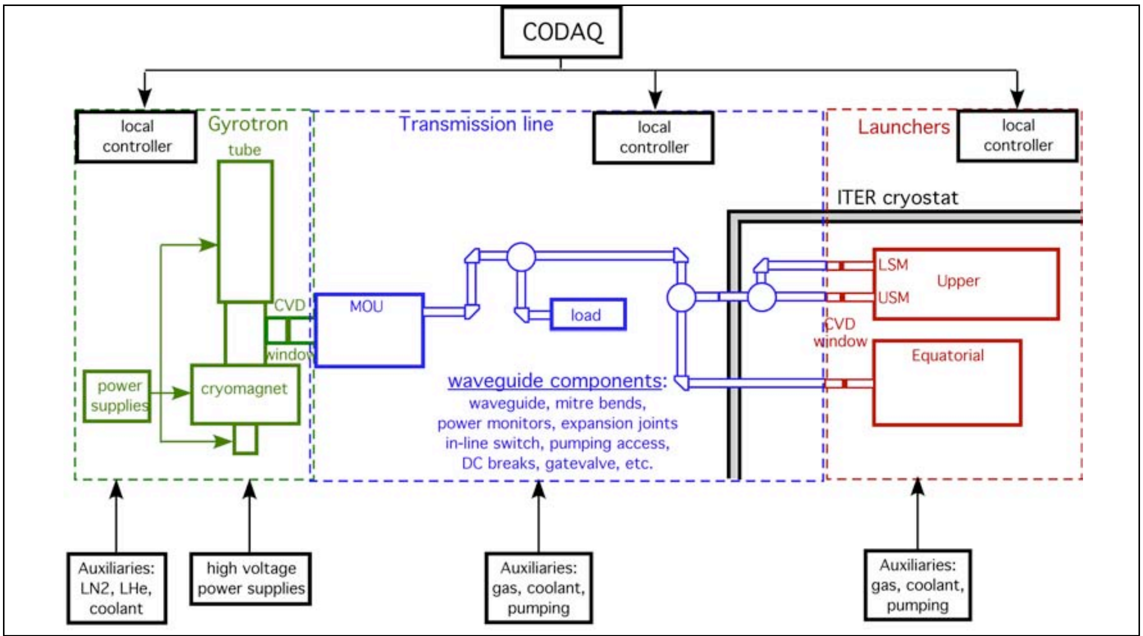

Figure 3.3 The present procurement boundaries for the EC system.

Traditionally, the MOU is delivered with the gyrotron or designed based on the available space around the gyrotron and cryomagnet. The supplier of the MOU will have to work in collaboration with all of the gyrotron and cryomagnet suppliers to insure that a MOU design can be obtained that is compatible with each gyrotron-magnet assembly. Realistically, this implies four different MOU designs, which increases the cost and complexity of the work required by the MOU supplier. Requiring the US to have strong interaction with the gyrotron suppliers (EU, JA, IN and RF).

The boundary at the launcher is placed prior to the diamond window component. Components prior to the diamond window will not experience the torus vacuum and can be made of aluminium rather than SS. There are several interface issues between the launcher and transmission line requiring a strong collaboration between the two suppliers. Issues concern safety (tritium boundary), torus displacements, specific launcher requirements, spatial restrictions, maintenance issues and launcher removal/installation. Requiring the US to have strong interaction with the launcher suppliers (EU and JA).

3.6.2 *Potential Boundaries based on ECH system*

An alternative procurement boundary that avoids some of the complexities described above is illustrated in figure 3.4.

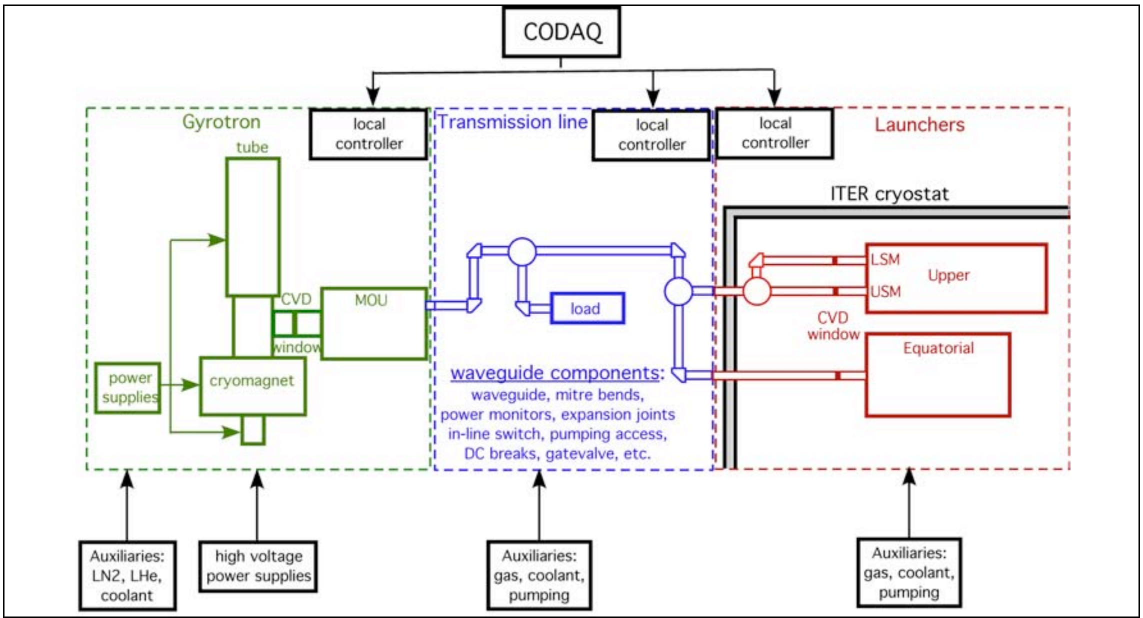

Figure 3.4 A proposed procurement boundary that avoids the superposition of the procurement and safety boundary at the launcher and places the MOU with the gyrotron.

The MOU can be delivered with the gyrotron such that each MOU is specifically adapted to each gyrotron-magnet configuration. The output beam description can be defined to insure high mode purity coupled into the waveguide.

The boundary between the transmission line and launcher could be moved to the cyrostat boundary. This would place all of the launcher integration issues (torus displacement, spatial requirements for maintenance and launcher removal, etc) under the responsibility of the launcher supplier. Also, it avoids having a safety boundary corresponding to a procurement interface.

Note such changes in procurement boundaries require negotiations between ITER-IT and the ITER partners.

4 Tritium barrier philosophy

4.1 Primary and secondary tritium barriers

The diamond window makes the primary tritium barrier, while the transmission line and relief valve makes the second barrier. The EU proposes an improved set of barriers as illustrated in figure 4.1:

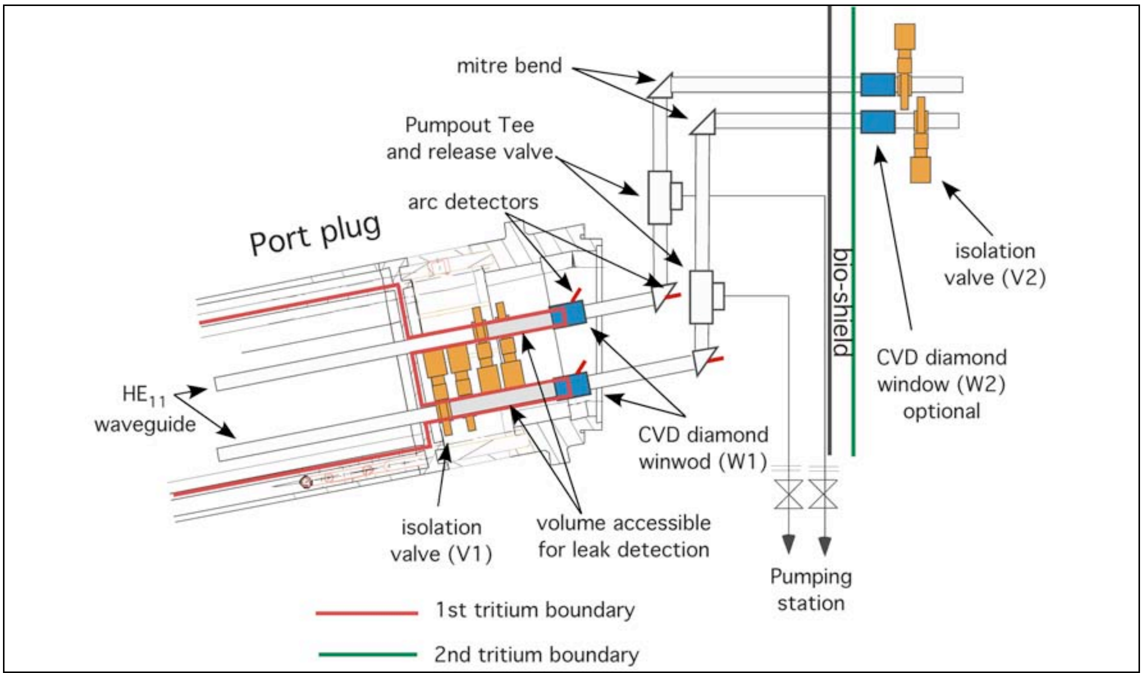

Figure 4.1 The proposed primary and secondary tritium barriers between the UL and transmission line.

An isolation valve (V1) is placed on the plasma side of the diamond window, allowing in-situ change and leak testing of the diamond window without affecting torus window. Also protects the window in case of an over pressure in the torus. The release valve can be included in the pump-out Tee (reduces overall costs). An isolation valve (V2) (and possibly) a second diamond window (W2) is placed at the cryostat entrance to avoid tritium leaking toward the gyrotron in case W1 fails. Additional vacuum pumping stations will be needed between diamond window and switching system (deviates RF power to UL or EL).

4.1.1 Release valves

The section of waveguide between the bio-shield and the diamond windows at the closure plate will need to be pumped, which can be achieved using a gap-type pump-out tee. A gap is made between two pieces of waveguide (as shown in figure 4.2) and enclosed around a cylindrical tube that is attached to a vacuum pump. The pumping conductance for a given gap of d_{gap} in an HE_{11} waveguide of radius a is given by:

$$C_{gap} \propto 0.1 \cdot \pi a d_{gap}$$

For a 6mm gap, the conductance is 57l/s, sufficient for evacuating the waveguide in this section.

The vacuum pumping section (see following figure) will also act as a pressure relief valve in the event that the diamond window bursts and a large pressure wave is sent down the transmission line. A majority of the pressure wave will be evacuated at the gap rather than traveling further down the transmission line. The conductances of straight HE_{11} waveguide of length L is given by:

$$C_{WG} \propto \frac{a^3}{L}$$

For a =30mm and L= 4m, the waveguide conductance is ~6.8liter/s (the conductance will be slightly lower due to the mitre bends). The ratio of conductances (C_{gap}/C_{WG}) is

>8. Since the pressure gradient is inversely proportional to the conductance, the majority of the pressure rise (which broke the 1st diamond window) will be attenuated across the gap and will not be seen by the 2nd diamond window (see next section for discussion on tritium barriers).

Note that the gap will also leak mm-wave power with the magnitude of the leaked power depending on the gap width; there is some optimum for a desired conductance while limiting the stray power out of the gap. A 6mm gap will radiate 175W, which can easily be absorbed by spraying TiO_2 (or other mm-wave absorbing material) on the inner surface of the vacuum enclosure as shown in Figure 2-5. Active cooling of the vacuum enclosure wall is envisioned to absorb the 175W. Note that GA has developed all of this technology.

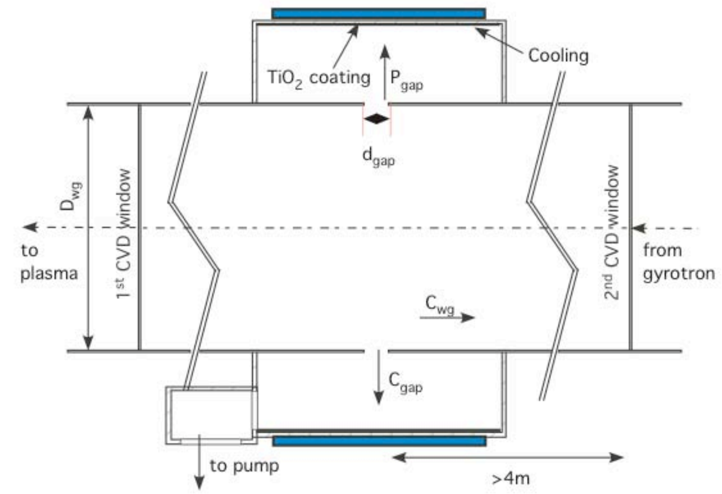

Figure 4.2 The gap type vacuum pumping waveguide component based on the GA design.

4.1.2 *Second diamond window and isolation valve*

Two failure modes are envisioned for the diamond window:

1) Crack formation leading to a small leak
2) Structural failure leading to a complete destruction of the window

The diamond window (1.11mm disk thickness) is rated for pressures of up to 3.5 bar, ITER requires the window to withstand a 2 bar over pressure. If the diamond window at the torus fails tritium could leak all the way up to the gyrotron diamond window. To reduce this risk an isolation (gate) valve is introduced in the line to limit the contamination.

In the event that the isolation valve fails to close, than there is a high risk that in the event of a diamond window failure, tritium will access all the way to the gyrotron diamond window. A secondary valve and/or diamond window could be installed at the cryostat boundary. The pressure wave that broke the first window would be strongly attenuated by the vacuum pumping section and the poor conductivity of the waveguide. It is unlikely that a pressure wave would provide an adequate shock to the second diamond window to cause a failure, since the waveguide conductance is so low (needs to be quantified). Note also that the diamond window unit could be made from the smaller 75mm diameter diamond disk (~30k€), which is approximately 70% less expensive than the larger ~105mm diamond disk used at the gyrotron.

Note that a full cost/benefit analysis including all safety implications has not yet been completed. This analysis should be performed in collaboration with ITER-IT and US DA.

4.2 In-situ leak testing

The UL is being designed to insure leak testing (and isolation) of all critical components (cooling and pneumatic actuator lines of the steering mirror, diamond window, etc.). In case a failure of one of these components, the component can be isolated and ITER operation continued with out requiring the launcher removed from the port plug. The in-situ leak testing of the diamond window requires leaking of a trace gas on one side of the diamond window and a mass spectrometer connected to the other side, see figure 4.3. This implies access to both volumes on either side of W1, thus the pump-out tee should be designed in light of this requirement.

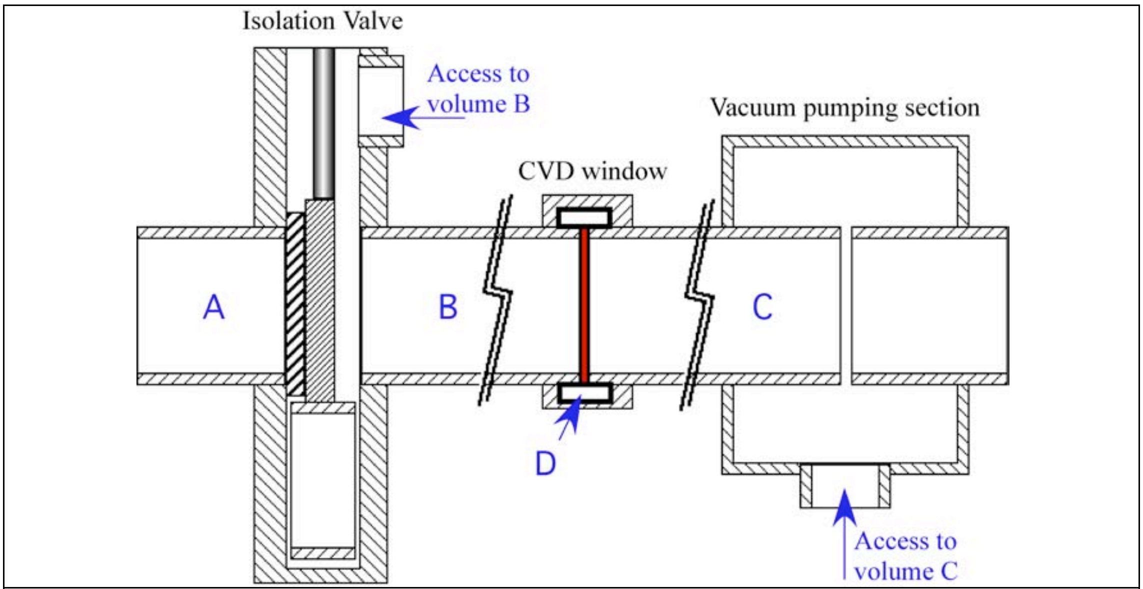

Figure 1.1 In-situ leak testing system for checking the integrity of the CVD diamond window.

4.3 Design implications to T-line and launcher

The proposed modifications to the tritium barrier will have an impact on the design and costs of both the T-line and launcher. The cost versus gain in security and potential cost of increased risk of tritium contamination in the transmission line are difficult to evaluate. The safety should be given a high priority.

5 T-line integration issues

5.1 Spatial considerations

The transmission line has to be designed to minimize the occupied space in the port duct area and avoid conflict with auxiliary systems for both the launcher and transmission line. Also, there will be components on both the launcher and transmission line that will require periodic maintenance (either human or remote handling) requiring a layout with adequate clearance for repair or replacement of these components. The additional switching system should be placed outside of the torus hall to avoid congestion of components close to the port plug entrance and for simplified maintenance access as discussed in section 2.4.3 The design needs to be done keeping in mind minimisation of dose to personnel.

The waveguide lines prior to the port plug could be integrated into a transportable crate that is removable prior to the removal/installation of the port plug. Removal would require disconnection of each waveguide (at the launcher and prior to the cryostat), cooling, vacuum, electrical and control systems. An alternative design would have the waveguide lines fixed to the sidewall of the port duct and then a 'dogleg' would bring the waveguides to the launcher entrance. Depending upon the space required for the transmission line and launcher removal system, this arrangement may require the removal of only the 'dogleg' assembly and disconnection of the waveguide and cooling lines prior to the port plug removal/installation.

It is critical that the transmission line design prior to the launcher is optimised for maximising access to the launcher and to the transmission line itself. This includes access for repair/replacement of individual components, of one transmission line section or the complete assembly. Also, access to the components of the launcher prior (gyrotron side) to the closure plate (in particular the diamond window and isolation valve) will be required for both hands-on and RH maintenance/replacement.

5.2 Torus displacements

The torus will displace due to thermal expansions/contraction during temperature variations, loss of coolant and during vacuum vessel outgassing. The PID estimates the torus displacements at various locations as shown in the following figure. For the waveguide prior to the upper launcher, there are two points of interest: edge of the port plug (VV-E) and the edge of the port duct (VV-E1) as shown in figure 5.1.

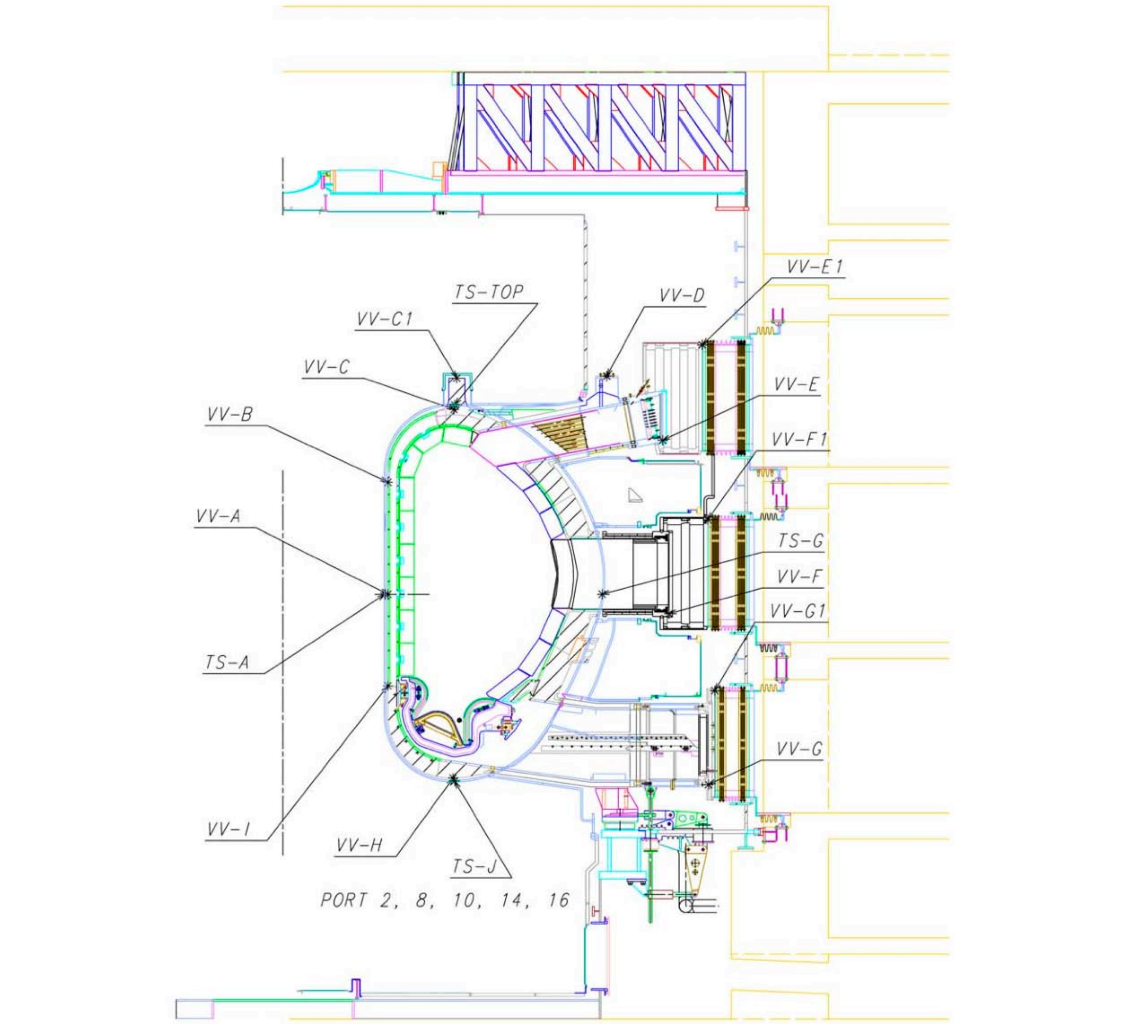

Figure 5.1 Poloidal cross section of ITER with selected reference points in which the torus displacement was calculated (figure taken from the PID)

The corresponding radial (ΔR) and vertical (ΔZ) displacements are given in table 5.1 for the torus at room temperature (T_{room}), nominal operating temperature (T_{oper}), baking temperatures (T_{bake}) and during coolant loss with all values relative to room temperature, note that the displacements associated with the vacuum vessel outgassing are less than that of the loss of coolant.

Table 5.1 The displacement of points VV-E and VV-E1 as a result of thermal variations and coolant loss, note that the displacements associated with changes in torus pressure are within the extreme displacements.

	(ΔR, ΔZ) @ T_{room}	(ΔR, ΔZ) @ T_{oper}	(ΔR, ΔZ) @ T_{bake}	(ΔR, ΔZ) @ Coolant loss
VV-E	(0.0, 0.0)	(16.5, 21.9)	(30.4, 40.5)	(43.1, 54.3)
VV-E1	(0.0, 0.0)	(19.3, 18.7)	(35.7, 34.5)	(50.6, 45.8)

For optimum transmission efficiency, the waveguide should be installed and aligned mimicking equivalent spatial conditions as if the torus is at T_{oper}. In this case the displacement amplitudes are measured relative to the conditions at T_{room}, as shown in the following table, with the magnitude of the displacements roughly halved relative to the zero position (see table 5.2) as compared with the displacements from room temperature (see table 5.1). The transmission line prior to the closure plate will be supported at the port plug end, in the port duct area and outside of the cryostat. The waveguide between each support will bend to accommodate the variation in the position of each support as the torus is taken from its operating conditions to some other state. Thus the waveguide will bend ~5mm (see row 'Δ' of Table 5.2) in both the radial and vertical direction between the port plug and port duct supports and ~30mm (see row 'VV-E1') from the port duct to the transmission line supports (located outside of the cryostat).

Table 5.2 The relative displacements if the waveguide is aligned at nominal operating thermal conditions.

	(ΔR, ΔZ) @ T_{room}	(ΔR, ΔZ) @ T_{oper}	(ΔR, ΔZ) @ T_{bake}	(ΔR, ΔZ) @ Coolant loss
VV-E	(-16.5, -21.9)	(0.0, 0.0)	(14.0, 18.6)	(26.7, 32.4)
VV-E1	(-19.3, -18.7)	(0.0, 0.0)	(16.4, 15.8)	(31.3, 27.1)
Δ	(2.8, -3.3)	(0.0, 0.0)	(-2.4, 2.8)	(-4.6, 5.3)

The waveguide will be made of aluminium in this region and can easily accommodate such bending. The stresses induced in a waveguide of diameter φ_{WG} (=63.5mm) will be within the yield strength for these small displacements.

5.3 *Launcher removal*

The transmission line prior to the port plug should be made in modular sections so that the components can be removed/installed easily in the event that the launcher has to be removed from the port plug. Note that the volume required in the port duct to remove the launcher is rather large and will have a significant impact on the transmission line design, as can be seen in figure 5.2 of the crate used to remove the port plug.

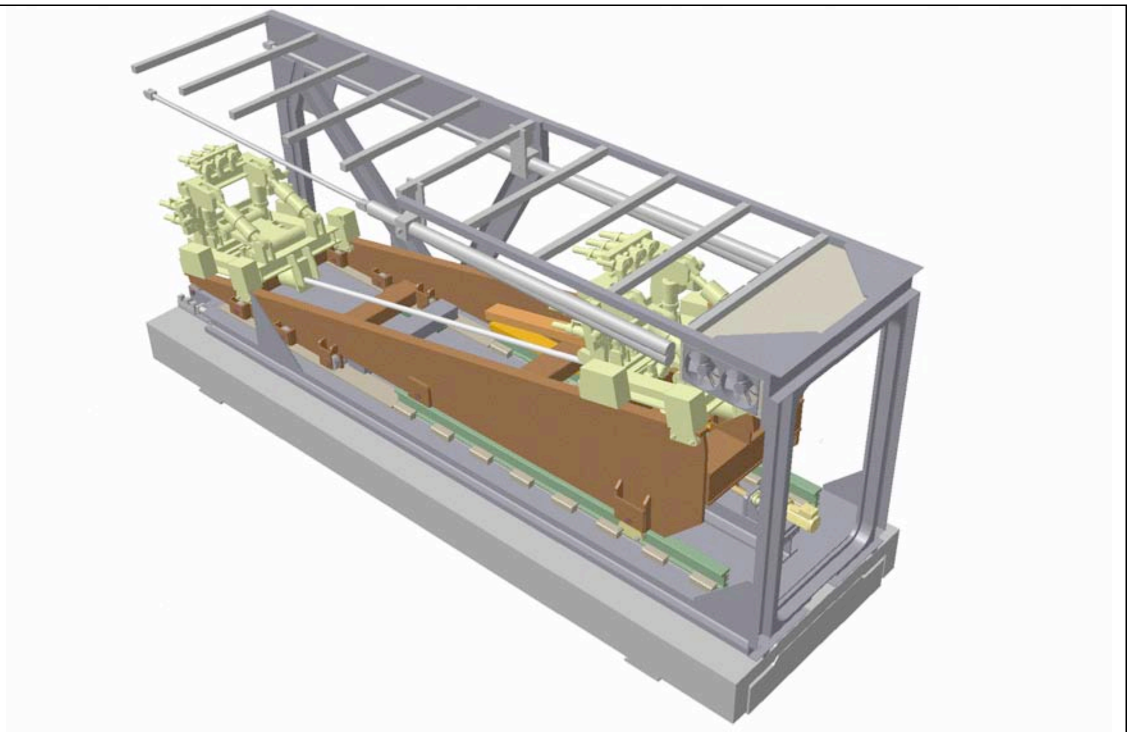

Figure 5.2 Crate used to remove the port plug and transport it to the hot cell.

5.4 *Diagnostics for T-line and launcher*

Some diagnostics on the transmission line will be used to evaluate the performance of the launcher. This includes mitre bend arc detectors looking into the launcher, vacuum diagnostics on the pump-out tee, etc. Some diagnostics will be common to both systems and should be designed with a common component strategy to reduce costs to US, EU and JA. Also, this will reduce the overall ITER operation costs have common replacement parts.

6 Launcher integration

6.1 *T-line to launcher connection*

The waveguide connection on the Launcher diamond window is to be made compatible with the transmission line waveguide connection. Standard GA connection with Helicoflex® seals are envisioned, as shown in the figure 6.1. Note that these connections only apply to the waveguide components that do not ‘see’ the torus vacuum. Connections of components that ‘see’ the torus vacuum are all welded.

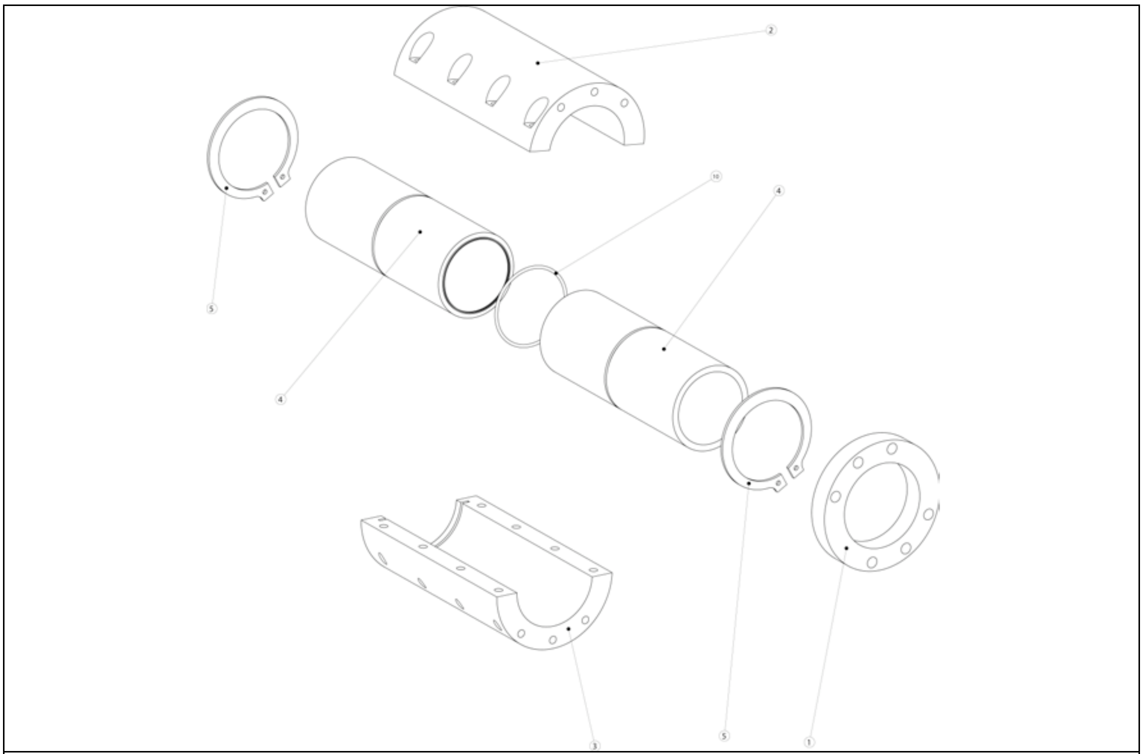

Figure 6.1 Waveguide coupling systems designed by General Atomics, which uses two half shells for alignment and a Helicoflex® seal.

6.2 *DC isolation*

The transmission line needs to be electrically isolated (~5kV DC) from the torus. An in-line DC break is commercially available with RF leakage within human safety requirements. The preferred location of this component is at the cryostat entry (only 24 DC breaks are needed, and keeps the line flexible near the torus for compensating for torus movements).

6.3 *Diamond window maintenance*

This includes in-situ leak testing (performed locally or remotely) and replacement of the window (activity that will potential result in the highest dose rates). Note that the replacement of the diamond window will be done manually with automated tools. Concept is briefly discussed above, we can provide some figures in the future for better understanding the problem.

7 Common component strategy

The common components located in the transmission line and either launcher should be designed to be interchangeable, which reduces the number of spare parts required and simplifies the ITER operation. In addition, the three ITER partners can benefit from collaborating/sharing analysis and testing. Component that are common to either launcher or transmission line include:

- *Straight waveguide*
- *Diamond window*
- *Mitre bends*
- *Isolation (gate) valve*
- *Diagnostic systems*

8 Conclusion

References