THE EC H&CD TRANSMISSION LINE FOR ITER

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The transmission line (TL) subsystem associated with the ITER electron cyclotron heating and current drive system has reached the conceptual design maturity. At this stage the responsibility of finalizing the design has been transferred from the ITER Organization to the U.S. Domestic Agency. The purpose of the TL is to transmit the microwaves generated by the 170-GHz gyrotrons installed in the radio-frequency building to the launchers located in one equatorial and four upper tokamak ports. Each TL consists of evacuated HE_{11} waveguides, direct-current breaks, power monitors, mitre bends, polarizers, switches, loads, and pumping sections and will have a typical length that ranges from 100 to 160 m. Overall transmission efficiency could be as high as 92% depending on the specific path between a given gyrotron and launcher. All components are required to be 2-MW compatible, and their layout and organization have been optimized for simplifying the maintenance accessibility and monitoring the primary tritium barrier integrity. Two different TL layouts are at the moment under study, to accommodate the two alternative options for the European sources: four 2-MW units or eight 1-MW units. In this paper the actual design is presented and the technical requirements are discussed.

KEYWORDS: *ITER, transmission lines, electron cyclotron heating and current drive*

Note: The figures in this paper are in color only in the electornic version.

I. INTRODUCTION

The ITER electron cyclotron (EC) heating and current drive (H&CD) system[1] is designed to deliver more than 20 MW of radio-frequency (rf) power at 170 GHz to the plasma. The EC system consists of rf sources, high voltage power supplies, transmission lines (TLs), and launchers: Up to 26 gyrotrons, fed by up to 13 power supplies, will be installed in the rf building. Of those 26 gyrotrons, eight units of 1 MW power each are procured in kind by both the Russian Federation and Japan, eight units of 1 MW (or four units of 2 MW) are procured in kind by Europe, and two units of 1 MW are procured in kind by India. Twenty-four TLs (procured by the U.S.) will run from the gyrotrons in the rf building through the assembly hall to the tokamak building where the TLs will be connected to one equatorial launcher or four upper launchers. The scope of the equatorial launcher is to provide central heating and current drive, while the four upper launchers with rf beam steering capabilities have the scope to provide magnetohydrodynamic instability control. Each TL includes at least two in-line switches, one to divert the rf power to a local dummy load for daily conditioning and a second to switch the power between the equatorial launcher and one of the upper launchers. The overall design has recently been optimized following

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changes in the interface with launchers and rf power sources, as well as a size reduction of the rf building where gyrotrons will be located.

In this paper, Sec. II gives an overview of the generic TL composition, its main purpose, and the technical requirements of its components. A brief description of the ITER TL evolution since its first design can be found in Sec. III, while Sec. IV describes two alternative TL layouts and the location of the components. Finally, in Sec. V the overall TL transmission efficiency is calculated, starting from published TL components' efficiency, followed by the conclusions.

II. TECHNICAL REQUIREMENTS FOR THE TL COMPONENTS

The main purpose of a TL is to transmit the rf power from the source to the launchers with the highest possible efficiency and mode purity. The specified power capability of a single EC TL is 2.0 MW for a pulse length of at least 3600 s with a 25% duty cycle. The required transmission efficiency is ≥90%. Besides this general scope, the different components of the TL subsystem have to satisfy a number of technical requirements. Each TL (Ref. 2) will consist of evacuated HE_{11} corrugated waveguide (63.5-mm inner diameter)[3–5] and various components distributed along the line. Corrugated waveguides have already been successfully used in several existing EC installations and have proven to be reliable for relatively high power, long pulse applications [DIII-D (Ref. 6), JT-60U (Ref. 7), LHD (Ref. 8), ASDEX-U (Ref. 9), TCV (Ref. 10), Tore Supra (Ref. 11), FTU (Ref. 12), T-10 (Ref. 13), Naka RF Test Stand (Ref. 14)]. These systems have been used as examples in establishing the ITER TL design, even if the ITER requirements are more demanding and challenging.

As already noted, the ITER EC H&CD system is going to be designed and procured based on a partnership between the ITER Organization (IO) and five of the seven Domestic Agencies (DAs) that constitute the international ITER project. Each DA is responsible for the procurement of a subsystem or a part of a subsystem, while the integration management and interface definition are the responsibility of IO. It is therefore of the utmost importance to clearly identify interface requirements and procurement responsibilities. With this in mind, it can be understood why the TL's boundaries have been defined adopting a slightly different definition than the usual. At the input, the TL begins after the Matching Optics Unit (MOU) output. In this way it is possible to define a unique requirement for the mode content at the MOU output (no less than 95% HE_{11}), equal for all gyrotron manufacturers. The MOU design is closely linked to the gyrotron's output beam characteristics, so it is more effective to develop a MOU together with its accompanying gyrotron. At the output, the TL ends at the flange prior to the diamond window, which is part of the launcher procurement arrangements. The reason to choose this boundary for the TL comes from the safety classification of the various components. The components from the diamond window up to the vacuum vessel closure plate form the primary tritium confinement barrier. Their safety classification is therefore different from the classification of the other TL components, since those are defined as belonging to the secondary tritium confinement barrier. This difference in safety classification implies different designs and quality assurance procedures. Splitting these TL sections into different procurements makes these differences more manageable.

The generic representation of Fig. 1 is useful to identify the TL interfaces with other EC subsystems, the interfaces with the buildings through which the TL is routed, and for capturing all components needed for satisfing the functional requirement of the ITER TL. A description of these components and their functions is as follows.

At the TL input a conflat adapter ensures vacuum tightness at the interface between the TL and the MOU. This component can be combined with an in-line direct-current (dc) break (which provides dc isolation from the gyrotron) and a taper[15,16] to minimize mode conversion losses at the transition from free space to guided beam propagation, i.e., a mode converter from TEM_{00} free-space mode to HE_{11} waveguide mode.

A change of propagation direction is realized by a mitre bend[3] (MB): a 90-deg corner piece that includes a flat mirror. Other functions can be integrated into the MB to minimize the number of TL components and the number of reflections (major sources of transmission losses). For example, the first MB of the line acts as power monitor[16]: an array of coupling holes is realized in the mirror surface to couple forward and reflected power into a set of WR-6 waveguides (~80 dB) for monitoring forward and reflected power in the TL. The second and third MBs have special mirrors to act as plane or elliptical polarizers[17]; these mirrors have $\lambda/4$ and $\lambda/8$ grooves, respectively, machined in the surface to provide control of the plane (and, respectively, ellipticity) polarization by rotating (90 deg in ≤2 s) the grating (in real time) about the normal surface of the mirror. The requested rotation ranges are $-90° \le \alpha \le +90°$ for the plane polarizer and $-45° \le \beta \le +45°$ for the elliptical polarizer. Most of the MBs will be equipped with arc detection systems (intervention time ~5 μs). In principle, it is possible to realize low-loss MBs (Ref. 16), equipped with input and output tapers and larger curved mirror instead of the standard flat mirror. These MBs generate less higher-order modes and have lower losses than the standard MBs, but they have larger dimensions and higher cost: At the conceptual design level, the standard components have been preferred, but during the preliminary and final design phases, a revision of this choice could be considered.

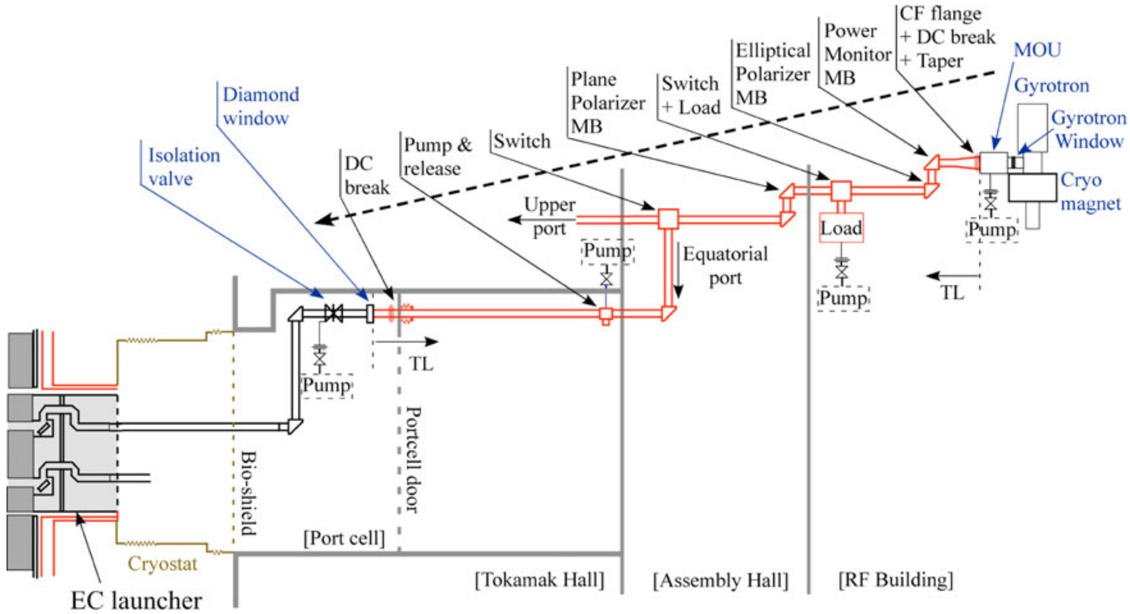

Fig. 1. Schematic of a generic TL.

An in-line switch[16] is used to alternatively transmit the power along the line or divert it to a dedicated dummy load, rated for continuous wave (cw) 1.5-MW power absorption. The cw load is used for daily gyrotron conditioning, recovery after gyrotron's internal arching, and during the commissioning phase. The TLs connected to the future European 2-MW gyrotrons will have a dedicated cw load with 2-MW power capability. A short pulse ($\sim$1.0 s) calorimetric load can be installed in place of the cw load for gyrotron installation and power characterization. A second in-line switch is used to direct the EC power to the common equatorial launcher (EL) or toward one of the four upper launchers (ULs). Switching shall occur in less than 2 s, in response to a change in physics requirements. These EL-UL switches are located along the wall between the assembly hall and tokamak building, where the distance between the axes of adjacent TLs is 300 mm (sufficient for maintenance). A compact design is therefore needed.

After the penetration through the south tokamak wall, a section of waveguide includes an in-line pump-out tee[18] that provides one of the pumping accesses to the internal volume of the TL (the other access being the MOU). This component also serves as a pressure releaser. A typical pump-out tee for a 63.5-mm waveguide has a conductance of $\sim$10 ℓ/s, and it has been calculated[19] that a small pump with pumping speed of $\sim$50 ℓ/s will be sufficient to evacuate the TL and maintain the required pressure level (pressure $< 10^{-2}$ Pa).

To provide 5 kV isolation from the tokamak, a second in-line dc break[3,5,18] is placed just inside the port cell. The tokamak building sits on seismic pads and is detached from the assembly hall; therefore, the TL section that bridges those buildings has to include a seismic break (see Fig. 2), a segment of waveguide that in case of seismic activity will compensate for the relative displacement of the TL tracts supported by the assembly hall's and tokamak building's supports.

III. TL DESIGN EVOLUTION

The entire EC H&CD system, whose design was initially outlined in 2000 based on technologies developed in the mid-1990s, has been significantly modified to adapt it to evolving technologies, to better satisfy physics requirements, and to optimize the overall layout.[20] This process also affected the TL subsystem so that in the period from 2007 to 2009, a number of changes were proposed and accepted. Following a rationalization path that led to the successful closure of the conceptual design review in June 2009, the handover of the design to the U.S. ITER Project Office (USIPO) was formalized in April 2010. USIPO is now responsible for completion of the design process, fabrication of the TL's components, and delivery to the ITER site. IO will then take over responsibility for installation and integration with the interfacing subsystems.

A brief discussion follows describing the major changes introduced in the TL subsystem during this phase of the design review.

The rf sources were originally located in the assembly hall, and the TL's routing required an excessive number of MBs. The creation of a dedicated rf building [shared between EC and ion cyclotron (IC) H&CD

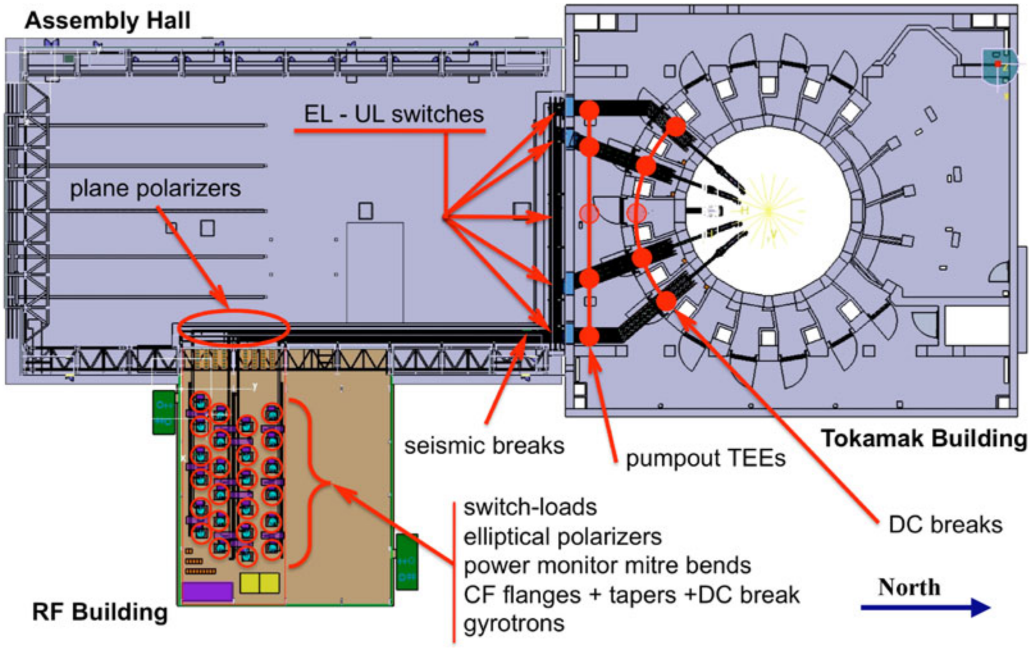

Fig. 2. EC H&CD system layout and TL components' location.

systems] allowed the optimization of the layout and reduction of the number of direction changes, decreasing the number of required MBs (each MB has an attenuation of about 0.02 dB, i.e., 0.5% losses). Once we chose the new TL layout, it was possible to design in detail the switching mechanism between equatorial and upper launchers that previously was described as generally a black box.

A rf conditioning unit (RFCU) was originally included in the TL scope and consisted of a switch to deviate the power toward a dummy load and four mirrors: the first couple designed to enhance the gaussian content of the gyrotron output beam followed by two polarizers (elliptical plus plane). The RFCU has been split in its functional components: a MOU that comprehends the first couple mirrors, an in-line switch, plus a dummy load and two polarizers.

The MOU has been moved to the gyrotron procurement scope, while the polarizers have been integrated in the second and third MBs, thus clarifying the requirement for the gyroton's output beam mode purity content and reducing the number of mirrors by two.

The diamond window, originally placed at the port plug closure plate, has been moved to the port cell where the larger interspace between adjacent TLs allows placement of the isolation valve and spacing optimization between critical components (~2 m between MB, isolation valve, diamond window, and dc break), reducing risks associated with higher order mode generation. As a consequence of this interface change, ~15 m of waveguides and 2 MBs have been moved from each TL to the interfacing launchers.

IV. COMPONENTS' LOCATION AND TL LAYOUT

Figure 2 shows the EC H&CD system layout and location of TL components for the case of 24 units of 1-MW generated power. It shows also the relative position of the three buildings spanned by the TL subsystem.

Note that the rf building size has been reduced since the original proposal, and now its dimensions are sufficient only to house the gyrotrons and power supplies for the initial 20-MW injected power of both EC and IC H&CD systems (Fig. 2 does not show IC equipments). Power supplies occupy the two bottom levels of the building, while the gyrotrons are installed at the third level and are arranged in four staggered rows of six units each.

The TLs originating from the same row of gyrotrons are grouped together in a two (horizontally) by three (vertically) arrangement. Each set of six TLs runs under the ceiling of the second level of the rf building, penetrates the east assembly hall wall, and bends north toward the tokamak building (see Figs. 3 and 4). Each TL connects a gyrotron to the EL and to one of the ULs. ITER port numbering increases counterclockwise (viewed from top), and EC power is delivered to upper ports 12 and 13, equatorial 14, and upper 15 and 16.

Along the east assembly hall wall, the TLs transition to form three rows of eight TLs each. A platform will be available for maintenance all along the assembly and tokamak walls.

At the corner between the east assembly hall and south tokamak building wall, top and middle rows comprise eight MBs each to direct the TLs west. The bottom

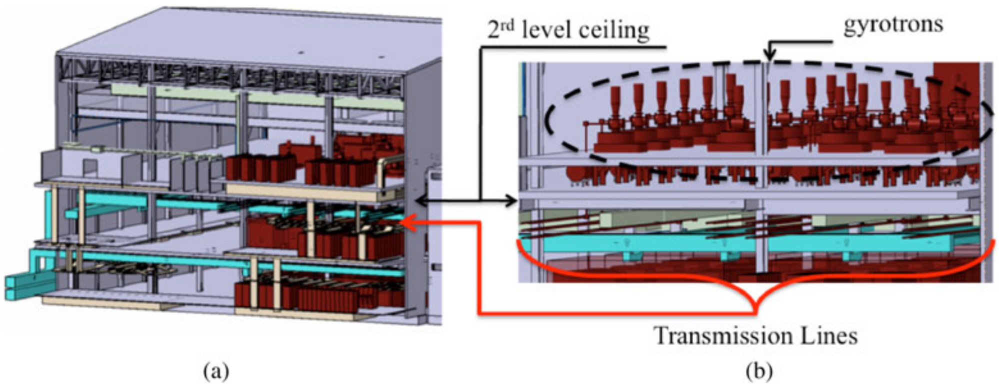

Fig. 3. (a) EC components' arrangement in the rf building at the intersection with assembly hall (not showed in the figure) and (b) detail of the TL routing under the ceiling of the second level.

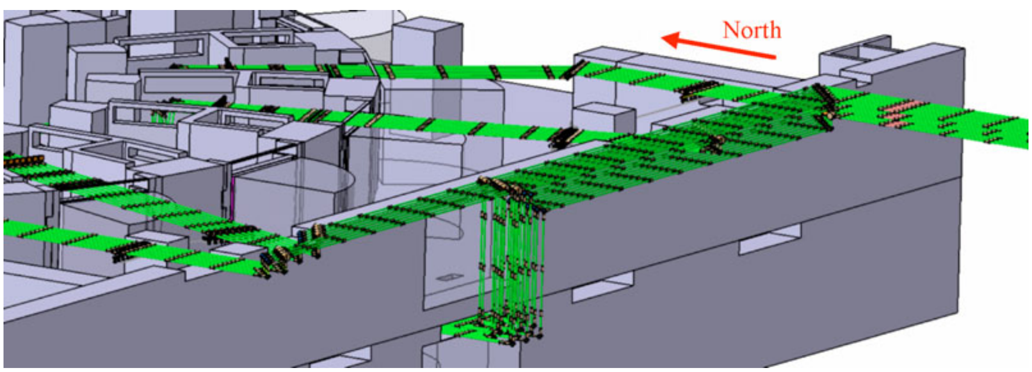

Fig. 4. TL routing along south tokamak wall and connections to upper port launchers.

row has a set of eight switches to route the power alternatively straight to UL of port 16 or westbound parallel to the other two rows and toward EL of port 14 (see Fig. 5).

In front of port 15, the middle row includes a set of eight switches to deviate the power to the corresponding UL or toward the EL of port 14. In front of port 14 (see Fig. 6), bottom and middle rows are connected to the EL

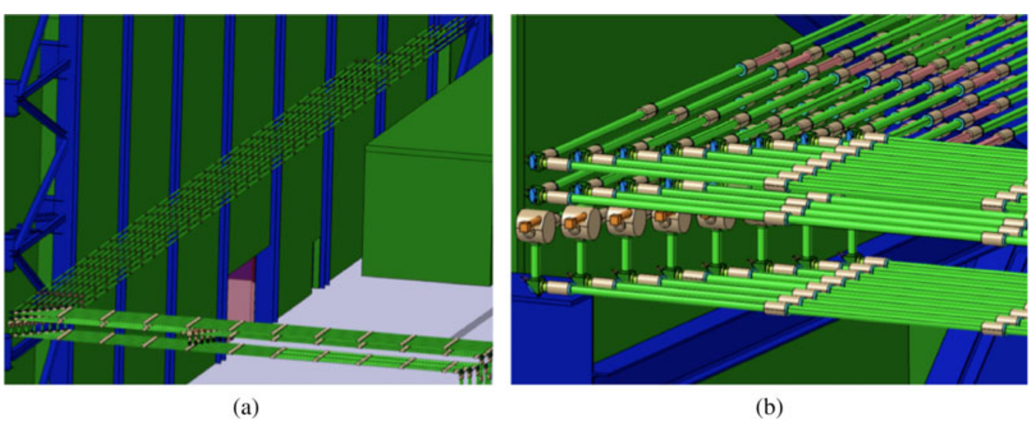

Fig. 5. (a) TL layout on the east assembly hall wall and (b) detail of the switches to port 16 upper launcher.

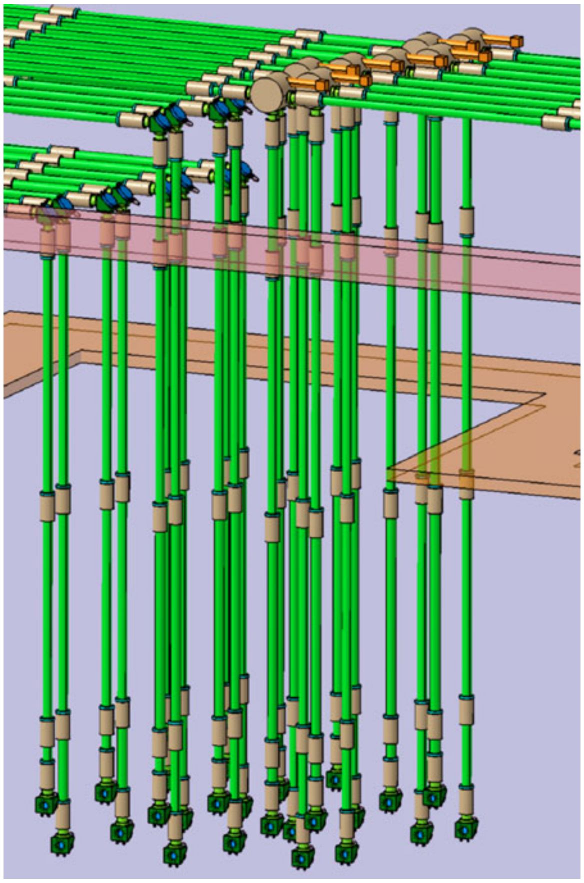

Fig. 6. TL connection toward port 14 equatorial launcher.

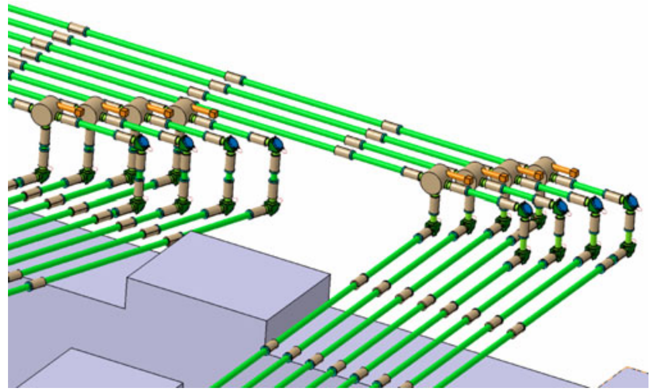

Fig. 7. TL connections toward ports 12 and 13 upper launchers.

through a couple MBs for each TL, while the top row includes a set of eight switches to route the power to the EL of port 14 or farther west: four TLs to UL of port 13 and four to UL of port 12. These last eight TLs each have an additional switch that allows alternative connection to the upper steering mirror or to the lower steering mirror of ULs of ports 12 and 13 (see Fig. 7).

Pump-out tees have been moved from the port cell area to the gallery, immediately after the penetration through the tokamak building south wall (see Fig. 8), to facilitate maintenance and connection to the service vacuum system. To cope with the nonorthogonal direction change required to route the TLs to UL of ports 12 and 16, a special 140-deg MB has been designed, and preliminary tests (not yet published) showed transmission losses comparable to the alternative solution realized using two standard MBs coupled in a periscope-like fashion. The special MBs will allow us to install closer to the ceiling the TL section connected to ports 12 and 16, thus offering greater compatibility with the penetration above the port cell door. On the other hand, the periscope-like solution has the advantage that only standard components are used. This is still an open point, and a decision will be made during the final design phase.

At the TLs input gyrotron side and just inside port cells, in-line dc breaks ensure 5-kV electrical isolation between TL, source, and launchers. While the final grounding scheme is still under discussion, the conceptual design requires TLs mutually electrically isolated and grounded at a single point in the rf building.

Pending the final decision about the 2-MW coaxial gyrotron development, an alternative layout for the European sources is presently also under consideration (see Fig. 9). The designated area for the 8 MW provided by Europe is the farthest from the assembly hall, where instead of eight 1-MW units, four 2-MW units will be installed. The space allocation is driven by the power supply located at the rf building's two bottom levels: Each power supply feeds two 1-MW gyrotrons or one 2-MW gyrotron. Moreover, sufficient space between gyrotrons has to be ensured because of the disturbance that mutual stray magnetic fields can produce. The TLs coming from the European gyrotrons can be reconfigured to be routed to the UL of port 15, ensuring the greatest flexibility of the overall system. The eight switches used to divert the power to the UL are to be rearranged in pairs to allow the alternative connection of each 2-MW unit to the upper or to the lower UL steering mirror following the same scheme used for upper ports 12 and 13. A three-dimensional model, with a configuration consistent with the gyrotron to launcher connection, has been developed.

V. TRANSMISSION LINE EFFICIENCY

Taking into account the illustrated composition and layout for the TL subsystem, an evaluation of the expected transmission efficiency has been performed, considering the latest published[3–5,17,18,21,22] attenuation value for each component. The highest and lowest transmission efficiencies have been calculated, respectively, for the TL connected to the UL of port 16 (110 m of waveguides + two standard MBs + one power monitor MB +

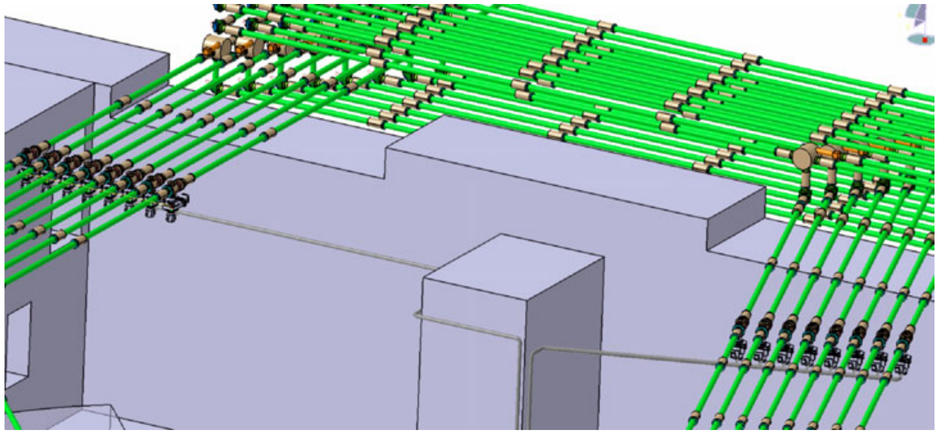

Fig. 8. New pump-out tee location close to tokamak building penetrations.

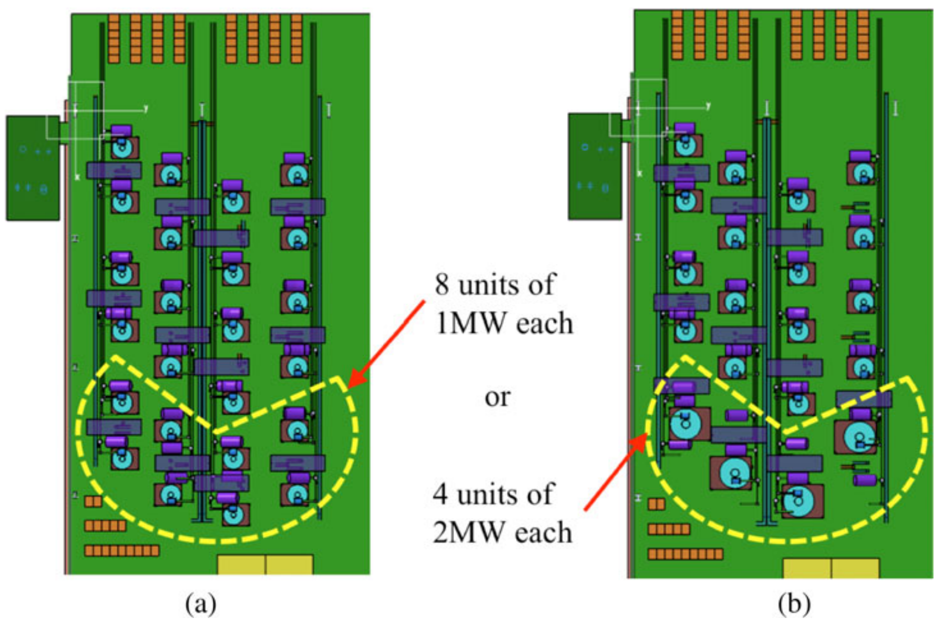

Fig. 9. Alternative layouts in the rf building for the European sources: (a) eight 1-MW units and (b) four 2-MW units.

two polarizers) and for the TL connected to the UL of port 12 (160 m of waveguides + five standard MBs + one power monitor MB + two polarizers). The TLs connected to ports 12 and 16 might have a special 140-deg MB instead of two standard MBs. Because no final decision on this point has been taken yet and the losses associated with the two configurations are comparable (see Sec. IV), for the present calculation the periscope-like solution has been considered. Including an estimation for the truncation losses at the TL input (~2%, to be considered only if the TEM_{00} to HE_{11} taper will not be installed)[16] and the unavoidable mode conversion along the TL (~3%) (Ref. 22), the calculated overall transmission efficiency is between 90 and 92% (see Table I).

VI. CONCLUSIONS

This paper has given a detailed overview of the ITER EC H&CD TL subsystem composition and of the technical requirements for the individual components. The changes and optimizations of the latest TL layout have been described together with the proposed solutions to accommodate the alternative European source configurations. The transmission efficiency of the actual TL arrangement has been calculated, using the available and published value for each component. It has been shown that a transmission efficiency between 90 and 92% is achievable, and therefore, the requested transmission efficiency is feasible.

TABLE I

TL Components' Attenuation Value and Estimate of Overall TL Transmission Efficiency

Component	Losses per Component	TL Composition (min to max set)	Total Losses (dB)
Waveguide (ohmic)[3–5]	0.015 dB/100 m	110 to 160 m	0.0165 to 0.024
Waveguide (mode conversion)[4]	0.02 dB/100 m	110 to 160 m	0.22 to 0.032
Standard MB[3]	0.02 dB	2 to 5	0.04 to 0.1
Power monitor MB[16]	0.02 dB	1	0.02
Polarizer[17]	0.034 dB	2	0.068
Pumpout tee[18]	0.0002 dB	1	0.0002
DC break[3,5,18]	0.00009 dB	1	0.00009
Total TL losses (dB)			0.166 to 0.244
Truncation losses (~2%) (without taper at TL input) (dB) (Refs. 15 and 16)			0.088
Mode conversion along TL (~3%) (dB) (Ref. 22)			0.13
Total (dB)			0.38 to 0.46
Transmission efficiency (%)			92 to 90

The present TL design has been found mature and validated through a conceptual design review process by an international panel and then transfered to USIPO for detailed design and fabrication. After delivery of TL's components to the ITER site, IO will take responsibility for installation, integration with interfaces, and commissioning.

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