EPJ Web of Conferences **313**, 04003 (2024) https://doi.org/10.1051/epjconf/202431304003
EC22

ITER ECH&CD Transmission Line Layout Development

Zachary C. Wolfe[1*], *Michael C.* Kaufman[1], *Aravind* Shanmugasundaram[1], *Gregory R.* Hanson[1]
[1]Oak Ridge National Laboratory, Oak Ridge, TN 37931, USA

Abstract. A primary contributor to the effectiveness of the ITER electron cyclotron (EC) heating & current drive (H&CD) transmission line (TL) is the distortion of the waveguide which has a strong, direct correlation with power transmission efficiency and electromagnetic mode purity. Two main sources of distortion are the deflection of the TL due to operational loads and misalignment of the waveguide supports. To address these and other interdependent variables, the EC TL design focused on a holistic method to provide iterative simultaneous development of the system and microwave components. The process provided close, rapid interconnectivity between the prescribed subsystem requirements and the design activities being performed, including a detailed 3D configuration management model, a system structural finite element analysis, a thorough multi-sample Monte-Carlo system functional performance assessment, and individual microwave component designs & analyses. This paper intends to provide an overview of the first of these: the design development process of the TL layout. This includes investigating the inputs into layout optimization, the overall integration process, the interconnectivity with the other design activities, and their impacts on TL subsystem performance that ultimately resulted in the current baseline layout.

1 Introduction

The physical routing of the ITER Electron Cyclotron (EC) Heating & Current Drive (H&CD) Transmission Line (TL) presents unique challenges to developing a resilient yet efficient layout. Physically, the TL is composed of 24 main runs that split, via a switching network, to 56 lines feeding 5 launchers. The system spans multiple buildings, is supported via secondary or tertiary steelwork depending on location, takes an indirect path from gyrotrons to launchers, and is composed of several thousand individual microwave components [1]. Meanwhile, operationally, the system is required to maintain a variety of high-performance characteristics, including high power transmission efficiency and mode purity, while dealing with the impacts from differential thermal behavior and support alignment & spacing.

With all these complex and codependent issues, a robust and integrated iterative design cycle was critical to the success of the TL layout development. This took the form of a holistic design approach that considered all layout inputs and processed the resultant TL behavior through a series of system- and component-level analytical assessments to determine the best balance between system performance, mechanical behavior, and general physical feasibility.

2 Layout Inputs

The transmission line layout is directly influenced by a bevy of layout inputs. These can be broadly categorized as 1) physical constraints and 2) operational constraints. Physical constraints are those imposed by the layout of the TL through the plant while operational are those imposed on the system via performance requirements. Both ultimately result systemic behavior that must be thoroughly considered.

2.1 Physical Constraints

The primary input dictating the TL layout is the physical routing as prescribed by the ITER Organization (IO) [2]. To minimize the impact of the tokamak's magnetic field on gyrotron performance, the system starts on Level 3 of the RF Heating Building (B15). Due to space constraints, the TL immediately drop from the 24 gyrotrons through the floor, turn west, and run along the ceiling of Level 2 before penetrating to the Assembly Hall Building (B13). In B13, the main 24 TLs turn north and run along the east wall until they reach the Tokamak Building (B11), where they turn once again and run west along the southern face of the B11. Via a switching network, the lines are split into 56 feed lines and run to either their respective upper launchers (one of four) or to the equatorial launcher, turning and penetrating both the B11 south wall and the related port cell lintels, both of which are safety-related secondary confinement boundaries. This tortuous path results in an average of 6 direction changes per TL run.

Challenges due to routing are amplified by the physical makeup of the supporting buildings. B15 and B13 are both braced steel structures, limiting TL support connection locations and increasing local effects due to large building deflections (e.g., B15 L3 deflects ~15 mm vertically from dead load only). This necessitates the use

* Corresponding author : wolfezc@ornl.gov

of tertiary steelwork to connect between the local TL supports and the building steel. In B15, the main TL runs hang from the ceiling, connecting to bridging members between the main building steel. Along the B13 east wall, the TL supports are cantilevered off the main building columns which have a 9.3-m center-to-center spacing, utilizing braced frame and hangers attached to runner beams.

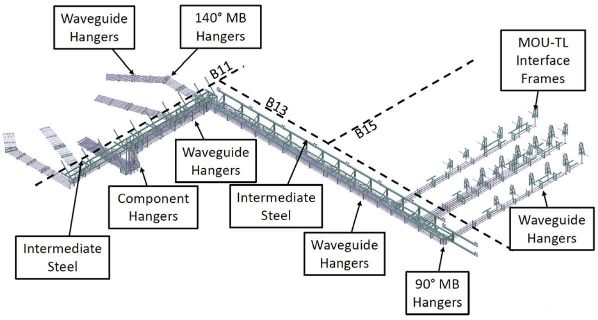

Fig. 1. ECH TL support scheme.

B11, meanwhile, is a reinforced concrete building. As the exterior constitutes a nuclear confinement boundary, post-installed anchorage is minimized and, instead, pre-installed embedded steel plates are utilized for attachment. This approach further limits connection locations. On the south wall a braced cantilever frame is used while inside the building the TLs are supported directly from the ceiling. In effectively all cases, the TL are supported from above and hang. This patchwork of building and structural support methodologies results in a complex supporting scheme with multiple locations along the primary load path for displacements, deflections, misalignments, etc., as shown in Fig. 1.

Compounding this issue is the foundation makeup of each building. All three buildings are on separate foundations. B13 and B15 are constructed on slab-and-footing style reinforced concrete foundations while B11 sits on a base isolation system to minimize the impact of accident scenarios, such as seismic excitation, from adversely impacting the tokamak. This has the unintended consequence of imposing large relative building displacements on the TL as it crosses from one building's load path to another, as shown in Fig. 2. These movements are generated due to daily and seasonal wind, differential thermal behavior, and seismic events.

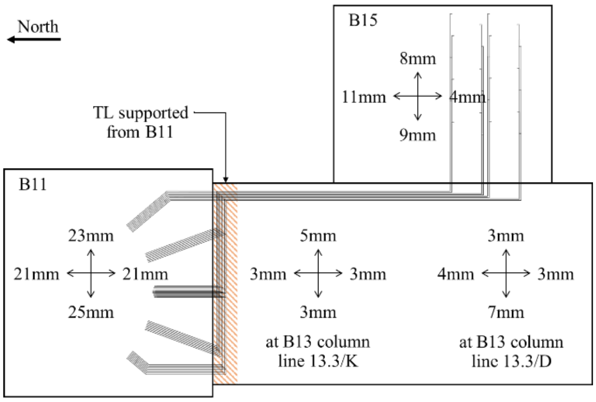

Fig. 2. Operational building movements (Cat.2) combined wind, thermal, and seismic.

Note that the values shown are for the Upset (Category 2) seismic condition. However, the TL is also required to maintain secondary confinement at the building penetrations and must therefore also consider Emergency and Faulted condition movements which are substantially higher (on the order of ±90 mm or more depending on direction).

Differential seismic excitation is also a main concern. For the Faulted condition, B11 can experience approx. 13 to 14 m/s^2 in horizontal seismic acceleration (in both directions) and upward of 38 m/s^2 in the vertical. Meanwhile, B13 and B15 both experiences approx. 14 m/s^2 in the horizontal but only 4 m/s^2 in the vertical. The dynamic interplay between these potentially opposing seismic spectra coupled with the related opposing relative building movement ultimately became a primary design driver.

2.2 Operational Constraints

Beyond the physical constraints of the routing, the TL must also consider a variety of parameters critical to system performance. From a layout standpoint, these are primarily thermal behavior during operation, support alignment, support spacing, and TL deflection.

While the TL is designed to be highly capable with a power transmission efficiency of ≥90% and an HE_{11} mode purity of ≥93% [3], approximately 1 MW of injected power per transmission line still results in nonnegligible thermal expansion during operation. With run segments more than 60 m and the TL thermally expanding at approx. 0.1 mm/m, even with all individual microwave components actively cooled via trace water line this thermal expansion, if uncontrolled, can lead to excessive TL deflection. This either compromises performance or, in more extreme situations, causes connections to mechanically fail. As such, proper thermal management was also a critical design driver to the success of the system.

Thermal behavior is addressed in two primary ways. First, a portion of the overall thermal expansion is handled via the introduction of active expansion units into the TL. These components expand and contract, utilizing a small gap within the microwave path to provide length compensation. However, expansion units introduce their own set of challenges in layout development. First, as the expansion units represent a physical gap within the TL, they are deleterious to overall performance, representing a discrete point of mode conversation whenever they are used. Therefore, their usage per TL run must be limited. Second, due to their inherent nature as an axially flexible part, the expansion units are mechanically weak in bending when compared to the other TL components. This further limited viable locations within a run as they must be located at low bending moment areas.

When expansion units are not sufficient to accommodate all thermal expansion, a second mechanism is employed: gross flexibility of the TL. By strategically locating structural supports along the runs, an arrangement can be found that limits the constraints placed on the system, allowing for a semi-free-floating routing. Ideally, limiting constraints permits the TL to find a more relaxed or stress-neutral position. For instance, allowing a miter bend to move by not directly supporting it but, instead, supporting the connecting waveguide nearby can help to dissipate internal thermal stresses by allowing the waveguide to deflect slightly. And example of the stress distribution of this approach at a miter bend is shown in Fig. 3.

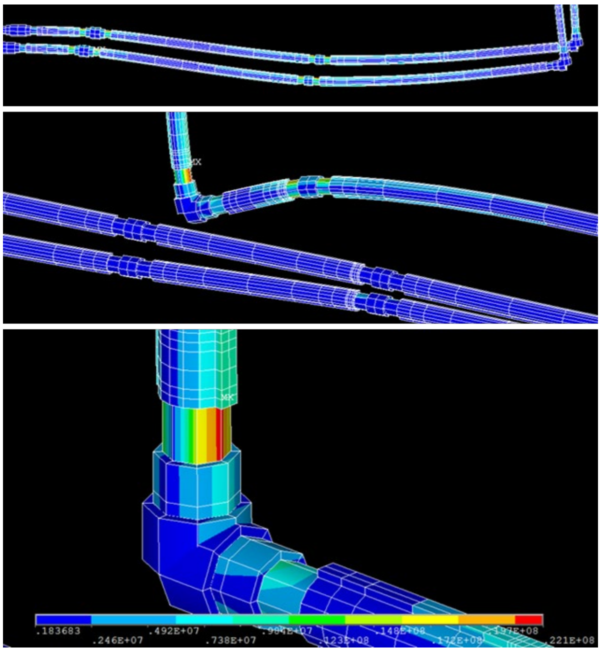

Fig. 3. Stress distribution due to gross deflection of the TL at a representative miter bend.

Support position also had to consider the impact of support-to-support alignment and overall spacing. While unrestrained in the axial direction (to allow for thermal expansion), the TL are typically restrained in the vertical and lateral directions. In this configuration, misalignment between supports along the axis of the TL introduces curvature into the waveguide as it subtly bends to adjust for this misalignment. This curvature ultimately results in additional mode conversation.

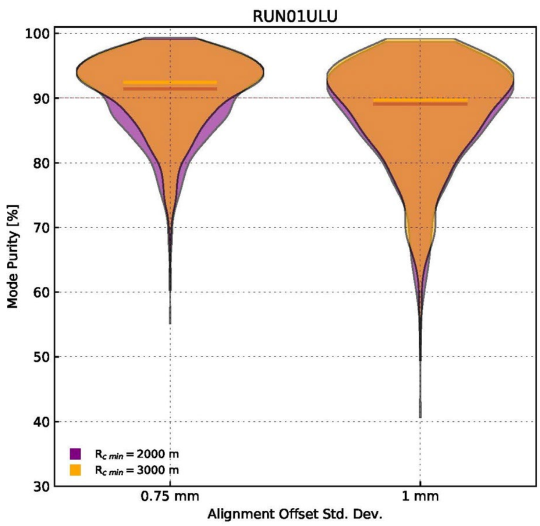

Fig. 4. Example of mode purity statistical distribution as a function of alignment offset.

Fig. 4 provides an example violin plot of the impact of support alignment offsets, comparing 0.75mm and 1mm standard deviations considering a manufactured radius of curvature in the straight waveguide sections at 2 km and 3 km. In this example, an 0.25-mm difference in alignment standard deviation results in a mean mode purity percent decrease of approximately 4% effectively regardless of manufactured radius of curvature.

This single parameter present throughout the entire system comprises roughly half of the entire mode purity budget. As this is directly affected by support position, adjusting support locations, spacing, quantity, and type (fixed, guided, gravity-only, etc.) became the largest lever used throughout the iterative layout development process.

As perfect alignment is impossible, supports are also ideally spaced as far apart as possible to increase the radius of curvature imposed on the waveguide. The further the supports are spaced, the lower the impact on mode conversion due to alignment. However, gross deflection due to self-weight of the waveguide quickly starts to control. Further, care must be taken to also avoid HE_{11} beat wavelengths. For 50-mm waveguide, if supports are spaced at approx. 3.2 m or 6.3 m these beat frequencies can be encountered, introducing extreme local mode conversion, as seen in Fig. 5. As such, a target spacing of approximately 4 m was selected as a compromise between all these factors. However, given the physical constraints previously mentioned, this was often not possible and smaller spacing was sometimes used.

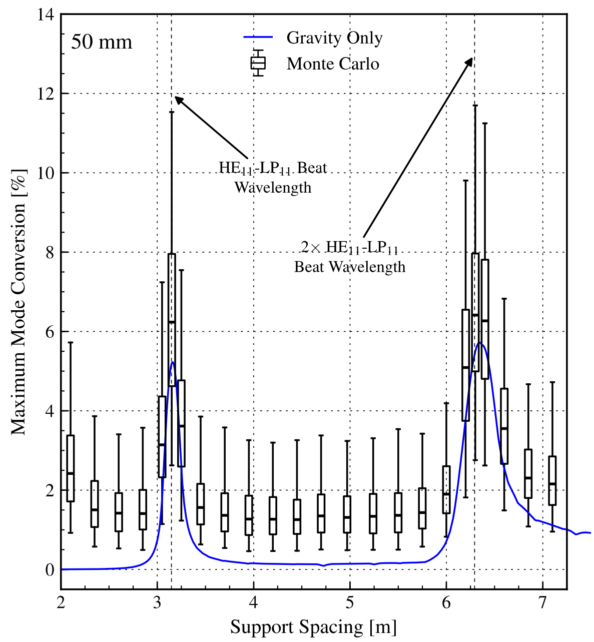

Fig. 5. Maximum mode conversion v. support spacing for 50-mm diameter waveguide, highlighting support spacings at HE_{11} beat wavelengths [4].

Ultimately, all operational constraints provide feedback into the physical deflection characteristics of the TL runs. This deflected shape directly impacted mode conversation and overall system performance and, as such, is the primary metric for assessing the viability of a particular TL layout scheme.

3 Development Approach

Early in the design development lifecycle of the TL layout, the interplay between all the physical and operational constraints was recognized. To maintain coordination and consistency between the various design and analysis activities, layout control tables were generated in Excel for each TL. These control tables provided all the layout data necessary to generate a 3D layout. They included all interface coordinates and direction changes (provided by the IO), component locations, support locations, etc. To maintain better control on coupling and support placements, these were manually input where necessary.

01ULL						
Component	Zone	Control Length	X [mm]	Y [mm]	Z [mm]	Support Ctrl Length
MOU	0		36400.000	-106943.000	12183.500	
POL	0		36400.000	-107443.000	12183.500	
WG	0	0.000				
SW	0		36400.000	-107443.000	10700.000	
WG	0	0.000				
POL	0		36400.000	-107443.000	9000.000	
WG	0	2875.000				2025.000
WG	0	2300.000				4000.000
EU	0					4000.000
WG	0	4200.000				4775.000
WG	0	3000.000				
WG	0	0.000				
MB	0		21000.000	-107443.000	9000.000	
WG	1	4200.000				700.000
WG	1	4200.000				2815.000
WG	1	3143.000				3500.000

Fig. 6. Example of a TL control table, running out from the Matching Optics Unit (MOU) toward launcher.

An example section of a TL control table is provided in Fig. 6. When a control length is listed as 0.000 for a waveguide straight (WG), the spreadsheet automatically calculates the required length given the lengths of the other WGs and the distances between miter bends (MB). If unlisted entirely, component lengths are driven from reference tables. Similarly, all component coordinates are calculated outside of those controlled via Interface Sheets (those shown explicitly listed in the table above).

While used for various follow-on tasks, such as the formal Bill of Material (BOM) generation and water-cooling routing checks, the next main step in layout development was to utilize the control tables to generate CAD rapid prototyping layouts. Via a combination of Excel and AutoCAD script files, the information in the control tables were parsed and converted into 3D .dwg drawings. While the formal CAD software for ITER is CATIA, AutoCAD provided a faster, lighter model that was primarily used to perform a visual assessment of the layout to circumvent any major errors prior to more formal publishing.

During this step, coupling placements were the first items checked. Couplings needed to avoid direct overlap with supports but also needed sufficient clearance for physical installation. In most locations, couplings in each TL array were aligned with one another on a plane perpendicular to the TL axis. This helped provide adequate clearance while allowing for gross control of both coupling & support overlap and coupling applied forces without having to micromanage each of the approximately 2400 couplings present in the system.

Couplings are also a source of mode conversion due to misalignment between the coupling components. While not as directly impactful as support misalignment, it was still important to attempt to minimize the number of couplings in the system, again due to how many there were. In combination with manufacturing tolerance studies, a maximum waveguide length of 3 m was selected, and this common length was used as much as possible. However, many locations necessitated smaller lengths and coupling placement was scrutinized to guarantee access and inspectability once installed.

Likewise, expansion unit placements were also assessed. Like couplings, expansion units were arranged in a perpendicular plane to better control applied forces. Their placements were strategically selected between adjacent supports to place them at zero- or low-moment areas. By maintaining a lower bending moment, the component didn't run the risk of becoming overstressed or binding when expanding or contracting. The installed neutral-position gap for each expansion unit was individually controlled. In most locations, ±15mm was used as this provided a good balance between thermal management, manufacturing tolerance stack up, and mode conversion. However, certain areas like the long run on the B13 East Wall or in B11 used, for example, +25 mm / -5 mm expansion units to provide additional thermal management at the expense of additional mode conversion. This balance was considered on a case-by-case basis throughout the entire system for all 56 runs.

While there were many other considerations during layout development, such as safety-related hardware locations and applied loads, gyrotron and ex-vessel waveguide interface management, RF load & feed waveguide arrangement, and the influence of auxiliary systems such as cooling water and instrumentation & controls, couplings, expansion units, and supports were the primary aspects manipulated throughout.

4 Process Integration

Once a given layout iteration was generated, the information was processed through a streamlined system of checks, assessments, and analyses to verify overall viability. The workflow generally went: Layout Iteration → Configuration Management Model → Global Structural Analysis → Functional Performance Assessment → Component & Support Analyses. Though it is important to note that as most activities were working from the same master set of layout date, these activities could often run in parallel until finalization.

4.1 Configuration Management Model

Maintaining configuration management within a shared 3D plant environment was paramount to the success of the TL layout development. This management was done utilizing a formal Configuration Management Model (CMM). A skeleton model – or a node-and-centerline model – was used as the underlying working file. While it allowed for quick and integrated work with the IO and other interfacing systems, the primary benefit was seen during internal work.

The CMM skeleton utilizes a parameterized coordinate-, plane-, and axis-driven model of the entire TL system, including all switch branches and local supports, that allows for dynamic modifications to the layout. This includes both global and local translational & rotational changes for individual components or entire TL lines. This greatly aided in rapid iterative design work and scoping activities within the physical plant space.

Each component is controlled by a series of nodes derived from the developing parts' dimensions and a central control node located along the axis of the TL. These node clusters can be placed on the TL centerline and oriented appropriately. Then, node-controlled 3D envelope models of the components are placed into the model with focus given to confined areas, such as switch arrays. An example of this implementation is given in Fig. 7. Planar and unique support locations, TL and individual component-volume and detailed space reservations, bills of materials, general arrangements, and isometrics drawings, etc. are directly generated from this graphical CMM data.

If discrepancies are identified – typically, clashes with other subsystems or misalignments with interfaces – they are fed back into the TL control tables for the next development iteration. Any modifications are therefore maintained at a central location, helping to guarantee consistency. After initial reviews are complete, the remaining component envelope models are inserted while analysis moves to the next steps.

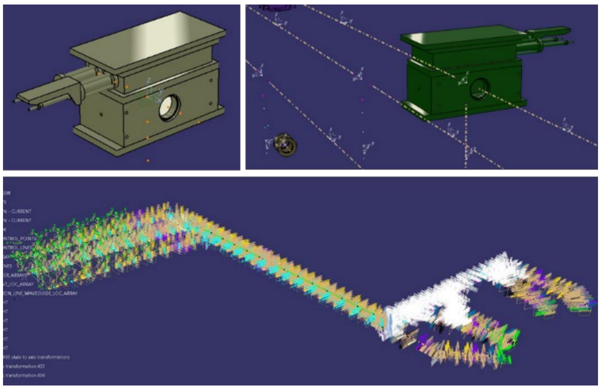

Fig. 7. CMM implementation example. Upper left: Switch envelope with control nodes. Upper right: Envelope placed on layout skeleton. Bottom: system with all skeleton points.

4.2 Global Structural Analysis

The primary function of the system global structural analysis was to assess the detailed behavior of the TL during normal and off-normal tokamak operations and events considering all applicable forces, including gravitational self-weight, absorbed microwave power & environmental thermal, atmospheric pressure (vacuum), relative movements between the three buildings due to daily and seasonal wind and thermal variations, seismic excitation, fire, and other accident scenarios. This detailed assessment is performed via finite element analysis (FEA) using ANSYS APDL [5].

Input files for this analysis are created with Python scripts using the TL layout data derived from the TL control tables, again maintaining consistency. For layout development purposes, the main output of this analysis was deflection characteristics during operating conditions, as seen in Fig. 8. In this example, areas of concern, specifically changes in direction or crossing of building boundaries, are immediately apparent with high deflections relative to the rest of the system. As deflection has a direct impact on TL performance, this analysis allowed the design team to better focus on areas needing attention, primarily by fine-tuning local TL support locations.

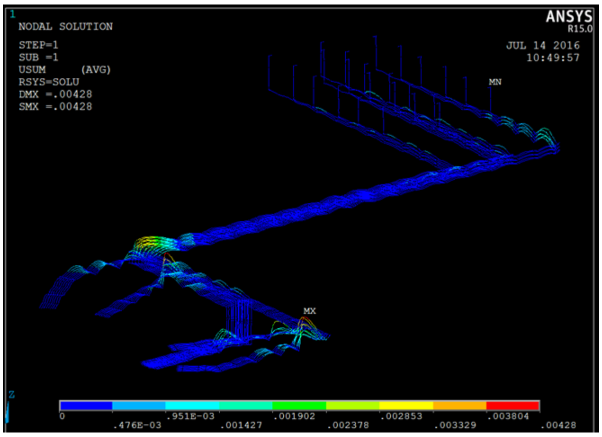

Fig. 8. TL deflection example.

Once the overall behavior of the TL was checked, the model was used to generate, via Python and APDL scripts, 1000 input files per TL run for the functional performance assessment of the system. These files provided the total deflected shape of the TL, including that generated through randomly simulated support misalignments. While not directly impactful to the mechanical or structural performance of the system, capturing support misalignment was very important to accurate performance analysis [4].

Finally, a more detailed assessment was performed to include off-normal and accident loads, as well, which further fed back into proposed layout changes. This analysis was used to generate individual component forces and helped determine support & interface reaction forces for use in developing final support designs. While this final analysis was underway, the functional performance assessment was performed.

4.3 Functional Performance Assessment

As mentioned, detailed deflection profiles from the system structural FEA for each of the 56 TL runs (56000 trials in total) were used as direct input for the functional microwave performance assessment of the system. Again, as the input information was generated directly from the ANSYS global structural analysis model, one-to-one consistency with the overall layout metadata was maintained. This integration also provided the most realistic representation of the physical behavior of the TL as installed and operated at the ITER facility, greatly increasing the overall accuracy of the expected performance [4]. An example trial output is shown in Fig. 9. From these trials and subsequent output data, problem areas within the layout could be identified.

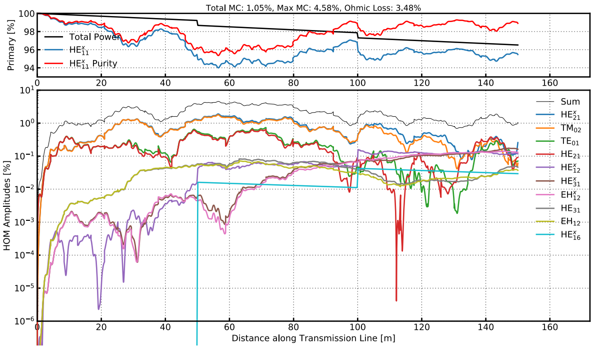

Fig. 9. Example TL trial performance characteristics as determined via detailed functional performance assessment.

4.4 Component and Support Analyses

The final step in layout validation was component and support detailed analyses. Individual microwave component analysis considers the various loads applicable to the part from both a performance and structural standpoint. From the TL global structural analysis results, applied loads are derived and used to verify the design of the component. As mentioned earlier concerning expansion units, local thermal effects from operations are often the main design drivers. Further, these deleterious effects were often seen specifically at miter bend couplings [6]. Substantial work went into to developing adequate expansion unit and support placements to minimize the loading on these couplings.

Likewise, system structural analysis results were used to design the physical support system, which must account for both local and global deflections of the TL to minimize performance impacts resulting from deflection stack-up. While TL support misalignment is handled statistically during the system's functional performance assessment, accurate calculation of the full support frame deflections is important for installation alignment. Due to the difficulties inherent in aligning the TL and the inability to reliably align the TL after the waveguide is installed, each local waveguide support (typically a guide) was designed to be individually adjustable. Using the calculated support deflection data for the TL and support self-weight, the guides are aligned high so that when the waveguide is installed the frame deflects down to its aligned position.

Like the overall design approach, there were numerous other considerations that were component- and support-specific. However, in general, applied loads and resultant deflections were the primary focus at the layout development level.

5 Performance Impacts

As the design team gained experience and major issues were identified & resolved, this complex iterative process grew increasingly efficient. Similarly, a more thorough, team-wide understanding of the interplay between the various design inputs and outputs – such as the criticality of support misalignments, the impact of thermal expansion on component coupling qualification, and the magnitude of reaction forces generated due to differential building movements – was further honed, streamlining the overall problem-solving approach.

This design effort, including the fine balance of all these disparate and often competing considerations, ultimately culminated in the current baseline layout which meets all prescribed performance requirements. It was presented at a final design review on March 2020 and was formally accepted by the IO and the design review closed out in February 2024 [7].

6 Acknowledgements

The authors would like to thank the entire ECH team, US & IO, for their hard work and dedication over the years to develop a work-class transmission line.

This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

References

1. F. Gandini, et al., "The EC H&CD Transmission Line for ITER", *Fusion Science and Technology*, **59**, 2011
2. Ronden, D.M.S., et al., "The Engineering Analysis in Support of the ITER Electron Cyclotron Heating and Current Drive Transmission Lines", *Fusion Science and Technology,* **59**, 2011
3. G. Hanson, et al. "ITER ECH Transmission Line System Design and Status", *Proc. of the 22nd Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating,* Daejeon, Republic of Korea, 2024
4. M. C. Kaufman, C. Lau and G. R. Hanson. Microwave Analysis with Monte Carlo Methods for ECH Transmission Lines. *Journal of Infrared, Millimeter, and Terahertz Waves.* **39**, 2018
5. A. Shanmugasundaram, et al., "Structural Analysis of the US ITER ECH Transmission Line System", *24th Topical Meeting on the Technology of Fusion Energy*, 2020
6. Claire Luttrell, et al., "Analysis of ITER ECH Transmission Line Waveguide Couplings", *Fusion Science and Technology*, **68**, 2015
7. N. Casal et. al., "Status of the ITER Electron Cyclotron Heating & Current Drive System." *Proc, of the 22nd Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating,* Daejeon, Republic of Korea, 2024