ITER ECH Transmission Line System Design and Status

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Abstract. The electron cyclotron (EC) heating & current drive (H&CD) system on ITER provides plasma heating by generating, transmitting, and launching high-intensity, high-frequency (170 GHz) electromagnetic wave energy steerable across the plasma cross-section. The transmission line (TL) subsystem connects the Matching Optics Unit (MOU) on each of the 24 gyrotrons to the 32 feed points in the four upper launchers and the 24 feed points in the equatorial launcher. Each TL must be able to operate at up to 1.2 MW of input power for up to 1 hour pulse lengths. The TL system contains 50 mm water-cooled corrugated waveguide, 90° miter bends, 140° miter bends, polarizer miter bend pairs, switches, expansion units, pumpouts, DC breaks, MOU-TL adapters, Radio Frequency (RF) loads, and isolation shutter valves. A detailed finite element analysis has been used to verify the thermo-mechanical performance of each component. The microwave performance has been analyzed using a 2-D electromagnetic code combined with a Monte Carlo code. This approach allows the impact of manufacturing and installation tolerances to be assessed and optimized to provide a high probability of achieving the system performance requirements. Prototypes of the waveguide and TL components have been fabricated and tested at high-power. Production contracts are now being issued for fabrication and delivery of the waveguide and components to ITER.

1 ITER ECH Transmission Line System

The ITER Electron Cyclotron Heating & Current Drive (ECH&CD) system is designed to deliver 20 MW of heating power to the plasma at 170 GHz with up to 3600 s pulse lengths. The transmission line (TL) system must transfer the power from 24 gyrotrons to 56 feed points on 5 separate launchers, while maximizing the power transmission efficiency and HE_{11} mode purity. Each gyrotron is connected to the Equatorial Launcher (EL) and to one of the four Upper Launchers (UL) by means of switches.[1][2]

2 System Description

2.1 Requirements

The primary ITER requirements for the microwave performance and functionality of the TLs have been defined as:

a. Each TL is required to have a power transmission efficiency of ≥90% to both the EL and the UL assuming 0.96 MW into the TL with 100% HE_{11} mode content.
b. Each TL shall have a median HE_{11} mode purity of ≥93% averaged over the 8 TLs per launcher assuming 0.96 MW into the TL with 100% HE_{11} mode content.
c. The TL shall be designed considering a nominal 1.0 MW gyrotron coupling 0.96 MW of total EC power into the TL with 0.912 MW in HE_{11} mode and 0.048 MW in higher-order modes at a frequency of 170 GHz ±300 MHz.
d. The TL shall limit the power associated to high order modes to 484 kW to any given UL as well as any set of 8 waveguides to the EL, equivalent to an average HE_{11} mode content of 92.8% defined as the median of the summed total power probability distribution of the operating transmission lines as determined by Monte Carlo input from the gyrotrons.
e. Each TL shall be capable of a pulse duration of up to 3600 s, a duty cycle of up to 25% assuming up to 1.25 MW at the gyrotron diamond window.

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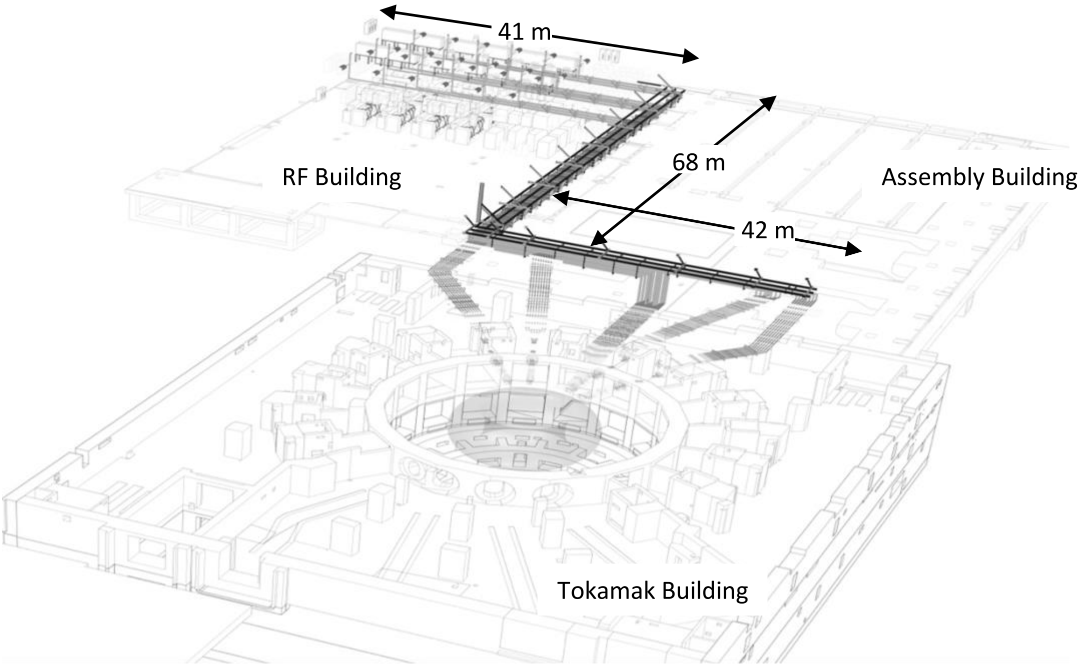

Fig. 1. Layout of the ITER ECH transmission lines. The transmission lines begin at the matching optics units (not shown) in the RF building, pass through the Assembly building, and end in the port cells in the Tokamak building. The ex-vessel waveguide (not shown) connects the TL to the launchers (not shown).

The TL polarizer miter bends shall provide a complete change in polarization in ≤3.0 s with a fractional power error of ≤ 0.1%.

f. Each TL shall be capable of independently redirecting its respective microwave beam between the equatorial launcher and associated upper launcher via an in-line, automatic, and remotely controlled switching system ≤3.0 s.
g. To support gyrotron conditioning, the TL shall include a dummy load and in-line switch with a power handling capability of 0.96 MW input power at a frequency of 170±0.3 GHz for 10 s.

The TL requirements were written to allow assessment of the TL performance independent of the gyrotron's performance or mode coupling to the TL. A Monte Carlo analysis, utilizing a 2-D electro-magnetic coupling code to propagate the microwave power down the TL while allowing alignment and manufacturing tolerances to be treated as variables, is used to assess the probable TL performance.[3]

2.2 Layout and Scope

The TLs run from the gyrotrons in the Radio Frequency (RF) Building (B15), through the Assembly Building (B13), and into the Tokamak Building (B11) as shown in Fig. 1. Each building has its own foundation, thus requiring the TL design to allow for the independent movements of the buildings during normal operations and seismic events. Additionally, buildings 13 and 15 are steel buildings, and the TLs hang of the steel beams and columns. The Tokamak building is concrete and sits on seismic isolators. This arrangement of buildings with the TL routed through all 3 buildings leads to a complex set of loads that must be accommodated in the design.[3]

ITER initially specified that the TL system utilize a 63.5 mm inner diameter (ID), but this was later changed to 50 mm to reduce the impact of waveguide curvature on mode conversion. Additionally, the ex-vessel waveguide (EW), which connects the TLs to the launchers and is under tokamak vacuum, was previously changed to 50 mm due to a reduction in the size of the available space for waveguide feedthroughs on the back of the port plug. Without changing the TLs to 50 mm ID, a taper would have been required in the EW just after the diamond window due to spacing requirements between the diamond window, miter bends and isolation valve. This would have created a risk of arcing at the diamond window due to standing waves.

The TLs start with the interface to the matching optics unit (MOU) and end at the interface to the EW in the port cells. The TL system uses the MOU-TL Adapter to form a vacuum connection to the MOU while providing ±5 mm of transverse and axial accommodation for MOU installation alignment, thermal expansion, and seismic movements.

The last component in each TL is the DC Break. The EW connects to the DC Break. The DC Breaks are rated to 250 V and interrupt conductive loops formed by the EW and the TL to prevent the creation of currents during disruptions.

Switches are used in B15 to redirect the power to RF loads. Switches are also used in B13 to switch the power between the EL and the ULs.

Expansion units are used to accommodate thermal expansion, building movements and manufacturing tolerances. The expansion units have a 30 mm stroke.

Pumpouts are used in B11 to connect each TL to the ITER service vacuum system (SVS). Additionally, ion pumps are used on the MOUs and the RF loads in B15. Due to the potential for tritium contamination in the TLs, vacuum pumps in B15 cannot exhaust to the environment. The ion pumps do not exhaust during operation. If regeneration is required, they will need to be connected to the SVS.

The TLs penetrations through the B11 wall and the port cell lintels are passages that cross the confinement boundaries designed to contain tritium and other hazardous materials. The TL uses an isolation shutter valve (ISV) to form a leak tight barrier. The ISV is also connected to the penetration to form a seal between the ISV body and the wall. The ISV is a fail-closed valve and is held open using compressed air. The ITER safety system can close the ISVs in a safety event. When the gate is closed, the ISVs limit the potential leakage of tritium through the TL, but the ISV is not a vacuum valve.

Waveguide, 90°, 140° and polarizer miter bends round out the components utilized in the TLs. The TL system, in its entirety, consists of 4028 m of WG in 1697 pieces of up to 3000 mm in length. The total scope of components is shown in Table 1.

Table 1. List of TL components and quantities.

Component	Quantity
Waveguide	1697
90° Miter Bends	120
140° Miter Bends	16
Expansion Units	160
MOU-TL Adapters	24
Switches	56
Pumpouts	56
DC Breaks	56
Isolation Shutter Valves	112
Polarizer Miter Bend Pairs	24
RF Loads	24

3 Integrated Design Approach

The TL design had 4 primary activities – detailed global model (layout), component design and testing, global and component finite element analysis (FEA), and microwave performance modeling. These 4 activities were performed in parallel with results from each feeding back to the others. The TL system FEA results can be found in [4], while examples of the component FEA can be found in [5-7].

The microwave performance analysis utilized a 2-D electromagnetic coupling code to propagate the microwaves through the TL in conjunction with a Monte Carlo analysis.[3] The code incorporated mode convertors and ohmic losses. Mode convertors included in the code are WG curvature, coupling tilts and offsets, miter bend mirror tilts and offsets, diameter steps, and gaps. WG curvature has 4 primary sources: residual curvature from manufacturing, misalignment of supports, thermal expansion, and gravity sag. Gravity sag, support misalignments, and thermal distortions are calculated using ANSYS and the TL global model, which also accounts for the location of supports. Optimizing support locations relative to couplings and components is critical to minimizing mode conversion.[8]

This Monte Carlo analysis was used to assess the manufacturing tolerances specified on the component fabrication drawings. Critical fabrication tolerances impacting TL performance included waveguide manufacturing curvature, coupling features impacting tilt and offset errors, and miter bend features impacting mirror tilt and offset errors.

To meet the steady-state ITER requirements, all components had to be designed with water cooling. The cooling had to be sufficient to minimize thermal distortion in miter bends, and sufficient to limit thermal expansion of waveguide to values that could be managed using expansion units.

3.1 Proof-of-Concept Prototypes

Fabricating prototypes has been a critical part of the TL development effort. During the initial design phase of the TL system, proof-of-concept prototypes were designed and fabricated to investigate manufacturing capabilities and what tolerances could be achieved on features critical to the TL performance. The tolerance information fed back into defining the tolerance distribution functions used in the Monte Carlo analysis.

These initial proof-of-concept prototypes had a 63.5 mm ID consistent with the ITER requirement for the ECH TLs at that time. The components, excluding the WG and ISVs, are made of CuCrZr, which has good electrical and thermal conductivity, has good mechanical properties (high strength), and has good machining properties. Prototypes of all components were fabricated, except for the MOU-TL Adapter. Figures 2–5 show examples of some of these prototypes.

The WG is made of 6061-T6 aluminum with copper cooling tubes clamped to the waveguide tube. Figure 6 shows the 63.5 mm ID prototype WG. The cooling tube clamps (top and bottom) assure good contact between the waveguide tube and the copper tubing. The clamps also increase the stiffness of the waveguide so that the deflections due to gravity are significantly reduced. A graphite-based foil is placed between the copper tubing and the aluminum WG to assure good thermal contact and to prevent corrosion.

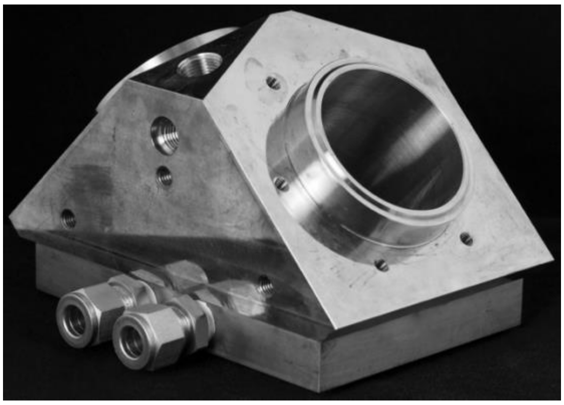

Fig. 2. Prototype 90º miter bend with a 63.5 mm ID.

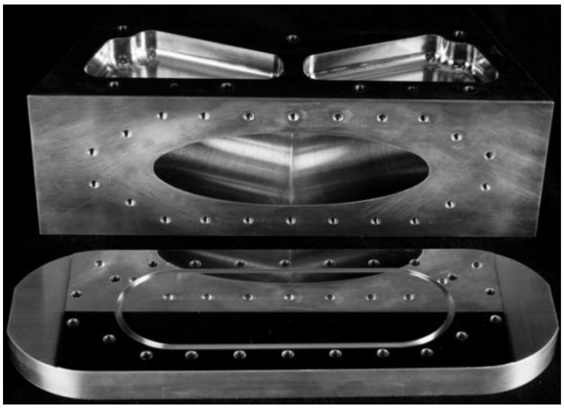

Fig. 3. Prototype 140º miter bend with a 63.5 mm ID.

Fig. 4. Prototype vacuum pumpout with a 63.5 mm ID.

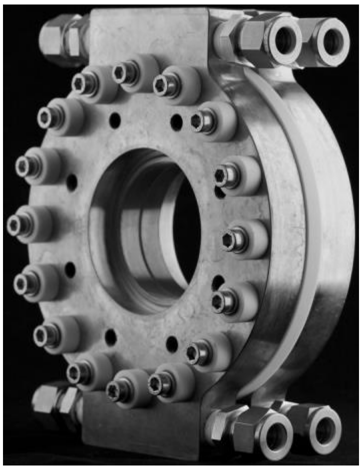

Fig. 5. Prototype DC break with a 63.5 mm ID.

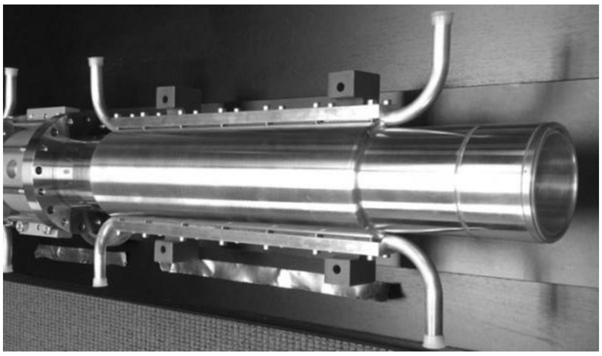

Fig. 6. Prototype 63.5 mm ID waveguide with clamp-on copper cooling tubes.

3.2 Final Design Prototypes

A second round of prototyping was performed after ITER changed the TL inner diameter to 50 mm. These prototypes utilized the ITER-approved final designs for the components. This prototyping effort is being used to qualify vendors for the production manufacturing of components for ITER. In some cases, two separate vendors were awarded prototype contracts to reduce the risk that a single vendor might fail at fabricating a prototype. Additionally, this allows for competition during the award of the production contracts.

Final design prototypes have been made for all components, except the polarizer miter bends and the ISVs. These components will have prototypes fabricated during 2024. These two components are being developed under contracts that include design and then prototyping. The RF loads have also been developed using design and prototype contracts. Two vendors have successfully delivered prototype RF loads and these two vendors are competing for the production contract.

4 High-Power Testing

All prototype components have been tested at high-power. The testing occurred in two phases. The initial testing was performed on the 63.5 mm ID prototype components and occurred at the National Institutes for Quantum and Radiological Science and Technology (QST) in Naka, Japan. The second phase of testing was on the 50 mm ID final design prototypes and took place at the FALCON ECH test stand at the Swiss Plasma Center (SPC) in the École Polytechnique Fédérale de Lausanne (EPFL).

The purpose of the high-power testing was to ensure no arcing or overheating occurred during high-power long-pulse operation. Infra-red (IR) cameras were used to monitor external temperatures. Visual inspection of the internal surfaces after the testing confirmed whether any damage occurred.

4.1 Testing at QST

The first phase of testing took place at QST between 2016 and 2019, and included prototype WG, 90° miter bend, 140° miter bend, expansion unit, switch, pumpout and DC break. All components were tested with pulses of up to 950 kW for 300 s. All components performed as expected, except for the pumpout.

The pumpout utilizes a honeycomb screen to prevent microwave power from getting into the vacuum pumping duct. This honeycomb screen absorbed a significant amount of microwave power, causing it to overheat and break. This indicated that the leakage power out of the corrugated portion of the pumpout significantly exceeded expectations. The leakage power and the vacuum conductance are proportional to the area of the corrugated surface removed to connect the corrugated volume to the vacuum port. The vacuum conductance was measured to be 40 l/s. The calculated conductance for the TLs on ITER is only 5 l/s. Having a significantly higher conductance on the pumpout would not improve the overall pumping speed on the TLs.

The pumpout design was modified to significantly reduce the corrugated surface area removed for pumping. A new prototype pumpout was then fabricated and tested to have a conductance of 5 l/s. This pumpout was then tested at high-power at QST and there were no further issues with overheating of the cutoff screen.

4.2 Testing at SPC

The second phase of testing took place at SPC in 2023. The gyrotron power varied from 650 kW to 850 kW with pulse lengths up to 1000 s. The testing included prototypes of the 3000 mm waveguide, 90° miter bend, 140° miter bend, MOU-TL adapter, expansion unit, switch, pumpout and DC break. Additionally, the RF load prototypes from the two manufacturers were tested. All components performed as expected. One test configuration is shown in Fig. 7.

The pumpout was setup with an IR camera imaging the cutoff screen through a vacuum window. This allowed monitoring of the heating of the cutoff screen. There was no indication of excessive heating.

The ITER TL test line at SPC saw more than 10 hours of integrate operation time at high-power during the commissioning of a new gyrotron. The test line components were inspected after this with no issues found.

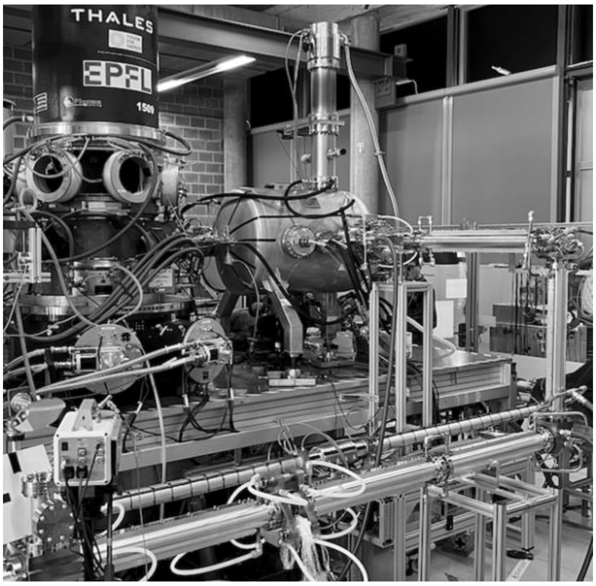

Fig. 7. A portion of the ITER TL test line at SPC. The MOU-TL adapter, waveguide 90° miter bends, and an expansion unit can be seen in this picture.

5 TL Status

The delivery to the ITER site has begun for the structural supports for the TL in the Tokamak building and the RF building. The design of the structural supports in the Assembly building will be completed this year.

Contracts for the manufacturing of all TL components have been issued, except for the waveguide, RF loads, and ISVs. Contracts for the waveguide and RF Loads are planned for award in 2024, while the contract for the ISV production is planned for 2025. The polarizer miter bends are being developed under a contract for design and prototype with an option for production. The first deliveries of waveguide and components are planned for late 2025 and continuing to the end of 2028.

6 ITER ECH Upgrade Impact

ITER is proposing an upgrade to the ECH system to increase the EC heating power to the plasma to 67 MW.[9] This involves increasing the number of gyrotrons from the baseline 24 to a total of 80. The upgrade would go in two phases with the first phase adding an additional 24 gyrotrons to the north end of the RF building. Phase two adds 32 gyrotrons to a new building east of the Tokamak building. Phase 1 is to be complete for first plasma, and phase 2 is to be complete for deuterium-tritium (D-T) operations.

This upgrade has a significant impact on the transmission line system. The baseline 24 TLs would be modified to go only to the upper launchers in ports 13, 15 and 16. The new 24 TLs coming from the north end of the RF building will go to equatorial launcher 14. The 32 new TLs coming from the new building will go to a new equatorial launcher in port 15 and to the upper launcher in port 12.

This upgrade is estimated to require an additional 6000 m of waveguide, 280 90° miter bends, 280 expansion units, 56 MOU-TL adapters, 56 RF loads, 48 ISVs, and 24 each of switches, 140° miter bends, pumpouts and DC breaks.

7 Acknowledgements

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References

1. M. Henderson, et al. An overview of the ITER electron cyclotron H&CD system. *34th IRMMW-THz*, 21-25 Sep. 2009, Busan, South Korea, IEEE, 2009
2. C. Darbos, et al. Status of the ITER Electron Cyclotron Heating and Current Drive System. *J. Infrared Milli and Terahz Waves*. **37** (2016)
3. 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)
4. A. Shanmugasundaram, et al. Structural Analysis of the US ITER ECH Transmission Line System. *24th Topical Meeting on the Technology of Fusion Energy*, 582-593, Nov. 2020, Chicago, IL
5. C. Luttrell, et al. Analysis of the ITER ECH Waveguide Transmission Line Expansion Unit. *Fusion Science and Technology*. **72** (2017)
6. J. Tipton, et al. Design and Analysis of 140-Degree Miter Bend for High Power Electron Cyclotron Heating Transmission Lines. *Fusion Science and Technology*. **72** (2017)
7. D. Youchison, et al. ITER ECH Switch Design and Analysis. *Fusion Science and Technology*. **72** (2017)
8. Z. Wolfe et al. ITER ECH&CD Transmission Line Layout Development. *Proc. of the 22nd Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating,* Daejeon, Republic of Korea, 2024 (to be published)
9. 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 (to be published)