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A study of mode purity improvement in the ITER relevant transmission line

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Abstract. In JAEA, mode conversion by corrugated waveguide system which is ITER relevant TL system was studied. To evaluate the alignment method for TL assembly, the mode content of middle section of TL was measured while assembly of the TL test stand. Then 5% of LP_{01} mode purity degradation was found in the long straight section though it was just assembly of 2m straight WGs. Indeed, the mode conversion calculation showed that 5% of mode conversion may occur when the straight section causes 1.0 mm of periodic deflection. To minimize the deflection, the alignment method with adjustment of both position and angle of the WG piece utilizing the laser beam reflection was applied for the TL re-assembling. The mode purity in the same section was improved and mode purity degradation was less than 1%. Finally 93% of LP_{01} mode purity was achieved at the end of long TL. Next the effect of mode purity by high-power long-pulse operation in TL was studied. Since the TL components are heated during the high-power RF operation, the TL causes deformation due to thermal expansion and deformed TL section induces significant mode conversion loss. The 170GHz gyrotron provided high-power (400kW) and long pulse (500sec) into TL and the beam profile at TL end was measured both before and after the long pulse operation. The mode purity at TL end was 91% before the long pulse and it decreased to 84% after the pulse. The temperature distribution and displacement of TL components were also measured. The measured displacement shows that the vertical sections became S-bend structures and mode conversion loss was estimated. The estimated total mode conversion loss in deformed long TL system was 8%. The estimated value showed good agreement with measurement of mode purity.

1 Introduction

The ITER electron cyclotron heating and current drive (EC H&CD) system is designed to inject 170 GHz / 20 MW millimetre wave power into plasma. The system is figured by RF power source, the transmission line (TL), the equatorial port launcher (EL), and the upper port launchers(ULs). RF power sources consist of 24 sets of 1 or 2 MW / 170 GHz gyrotrons which will be installed in the RF building. A set of two gyrotrons will be operated by a single main high voltage power supply (HVPS) and two sets of acceleration grid power supplies: body power supplies (BPS) and anode power supplies (APS) for triode gyrotron. EU, Russia, and Japan procure 8 gyrotrons[1-3] and EU and India procure 8 and 4 sets of power supply systems. RF power from gyrotron is coupled into TL to transmit from RF building to launchers on the vacuum vessel. TLs are composed of corrugated waveguide system of 63.5 mm inner diameter including miter bends, polarizers, waveguide switches, and high power dummy loads. The waveguide switch in TL changes the RF power direction to UL or EL. Each line is designed to transmit 1 or 2 MW RF power for 100 m distance.[4] 24 TL for each gyrotron system will be procured by US. Single EL procured by Japan and 4 ULs procured by EU will be installed into the equatorial port and the upper port of ITER vacuum vessel.[5-7]

The improvement of transmission mode purity in TL is one of the key issues in ITER EC system. Since all the EC components in ITER are designed to minimize its loss to achieve the specification in ITER, high mode purity is strongly required.[8] In JAEA, the transmission mode content measurement and coupling method from gyrotron to TL were studied and we succeeded to couple gyrotorn RF power to TL at 95% of $LP_{01}(HE_{11})$ mode, the fundamental transmission mode in corrugated waveguide, which achieved the requirement for RF power coupling in ITER.[9] The TL system and its components for ITER are also widely studied and some theoretical and numerical studies even presented the transmission efficiency of mode content in ITER TL.[10-12] JAEA has ITER relevant TL test stand and some ITER TL components were examined for high-power operation using 170 GHz gyrotron. This report presents the result of

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mode content measurement in the JAEA TL test stand and the effect of high power long-pulse operation in TL.

2 JAEA TL Test Stand

The high power test stand of ITER relevant TL composed of 63.5 mm corrugated waveguides and TL components was examined with 170 GHz gyrotron in JAEA.[1,13] The TL input is connected to output of matching optical unit (MOU) which couples RF beam from the 170 GHz gyrotron into waveguide. The TL test stand consist of the short TL (7 m) with a terminal dummy load and the long TL (40 m) which delivers RF power to another dummy load and EL mock-up. The test stand includes 5 miter bends, two waveguide switches, and a polarizer. The first waveguide switch (WG-SW-I) selects the short and long TLs and the second waveguide switch (WG-SW-II) selects the dummy load operation for long TL and equatorial launcher mock up. Dummy loads utilized in the test stand are designed for 1 MW-long pulse operation. The TL test stand also includes two waveguide gate valve to isolate the short TL, the long TL, and EL mock-up. The schematic figure of the TL test stand is shown in Fig.1. All miter bends, polarizer, and WG-SW-1 utilized for the experiment are product of General Atomic.[14]

The measurement of mode content in TL waveguide was carried out in the test stand. For this purpose, the RF filed profile of the radiated beam from waveguide outlet was measured using a screen and a thermal imaging camera. RF filed profiles at different positions were obtained and phase retrieve analysis was applied for measured data. The complex field profile at waveguide outlet was deduced. Then mode content at the waveguide was deduced using the complex field profile.[9] Since the gyrotron provides linearly polarized RF beam, the transmission mode content in the corrugated waveguide of TL is able to represent in Linearly Polarized modes (LP mode), such as LP_{01} mode which represents HE_{11} mode.[10] In this study, the polarizer in TL was settled to keep linear polarity during the experiment and mode contents are described in LP modes.

3 Mode Conversion in straight section of TL and Assembly Method

The measurement result indicates that mode conversion loss by transmission components like miter bends generates LP_{11} mode and it propagated to TL end. Thereby although good mode purity was achieved at the high efficient beam coupling, the mode conversion loss in TL components becomes source of LP_{11} mode.

The source of mode conversion loss in TL. Miter bends are expected the major source of mode conversion in TL. Olstad et al reported the single miter bends causes 0.42 % of mode conversion from LP_{01} mode to LP_{11} mode with 0.05 degree of misalignment of miter bend mirror.[11,14] The waveguide sag due to gravity and junction error also cause mode conversion in TL. Shapiro et al. reported the total mode conversion loss in ITER TL (125 m) caused by these effect is -0.075dB.[12] The loss value expected for JAEA TL test stand is 0.5 % according to the report.
Indeed the waveguide may have larger curvature than gravity sag due to wrong assembly process for instance. When the curvature of waveguide appears periodically, the mode conversion increases than the case of single curved waveguide. Since the TL is usually assembled with 2 m-piece of waveguide, the periodic deformation may appears even in straight section of TL where the mode conversion loss is expected very small.

The mode conversion in the straight section of TL with periodic deformation was estimated. The total amplitude of deformation *D* was varied from 1.0 mm to 3.0 mm. The deformation and mode conversion was plotted in Fig.2. The result shows that 5% of mode conversion may occur when the straight section causes 1.0 mm of periodic deflection.

In JAEA, the laser aligner is utilized for the alignment of waveguide during TL assembly. The aligner was

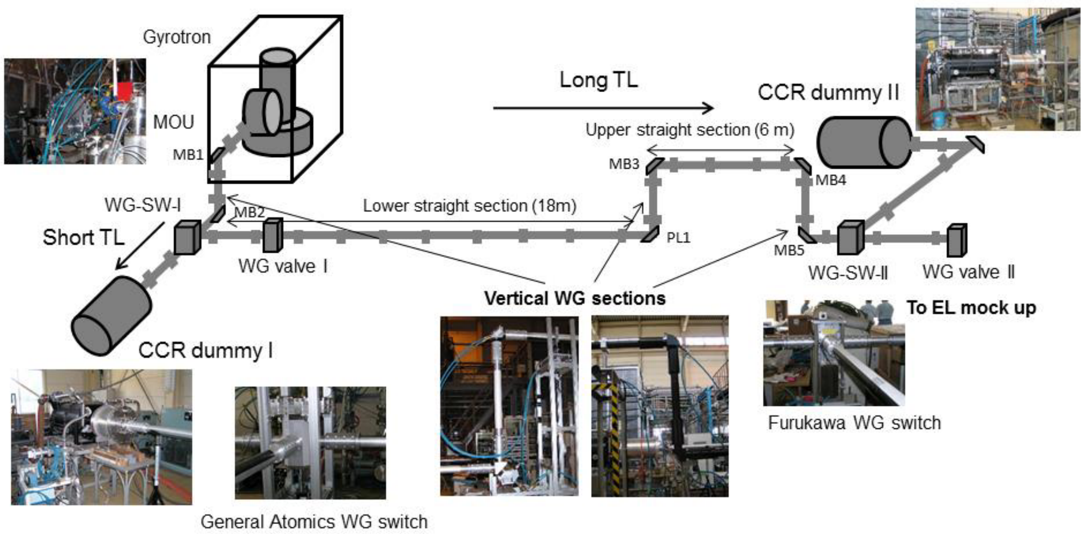
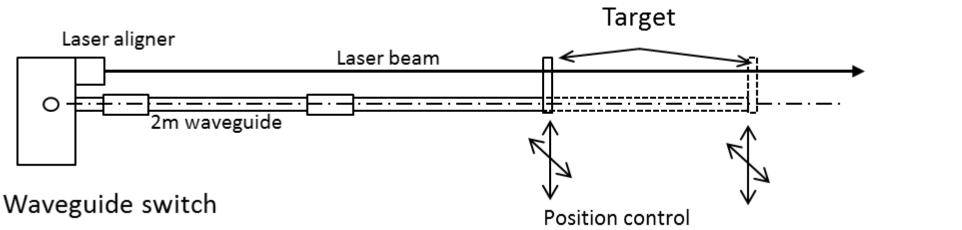
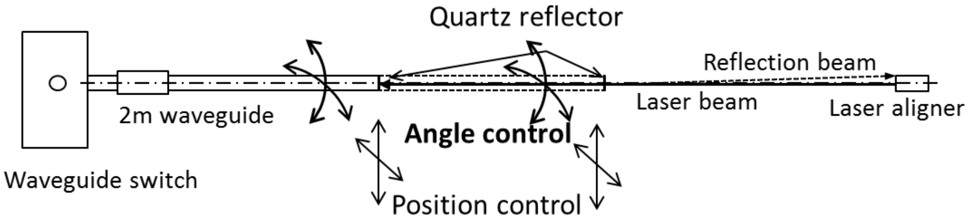


Figure 1. Schematic figure of JAEA ITER relevant TL high-power test stand.



(a) Position control method



(b) Position and angle control method

Figure 3. TL component alignment method to TL assembly using a laser aligner

settled on the start point of the straight section of TL and laser beam provide the track for straight section line. Waveguide pieces were connected to each other to keep straight line by measurement of laser beam position at each waveguide end as shown in Fig.3 (a). This method controls positions of waveguide coupling point, namely position control method.

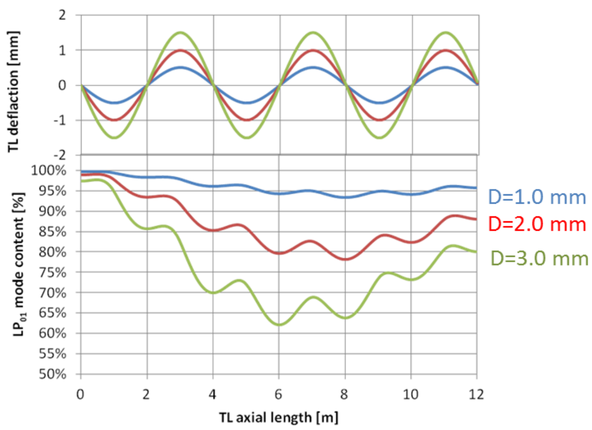


Figure 2. Mode conversion calculation for periodic deformation of straight TL section. Calculation result includes *D*=1.0, 2.0, 3.0 mm case.

While assembly of the TL test stand with position control method, the mode content of input and end of the straight section was measured. The result was listed in Table 1 and 5% of mode purity degradation was found in the 12 m length line though it was just assembly of 2m straight WGs.

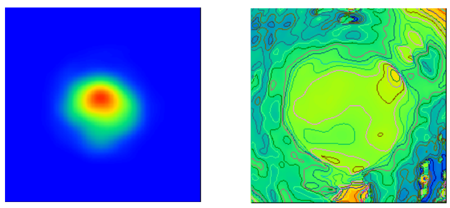
To minimize the deflection, the alignment method with adjustment of the position and angle of the WG piece utilizing the laser beam reflection as shown in Fig.3 (b) was proposed and it was applied for the TL re-assembling of straight section. The mode purity in the same section was measured as listed in Table 2. The mode purity at output of straight section was improved and mode purity degradation was less than 1%.

Table 1. Mode contents in input and output of straight section of TL assembled with position control method.

Mode	Input	Output
LP_{01} (HE_{11})	95.7 %	90.9 %
LP_{02}	0.3 %	0.9 %
LP_{11}(o)	0.9 %	0.4 %
LP_{11}(e)	0.8 %	5.4 %

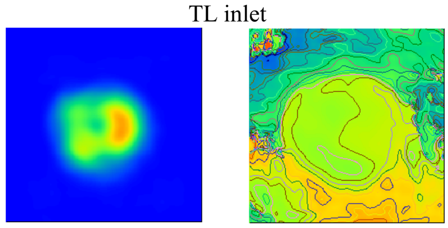
Table 2. Mode contents in input and output of straight section of TL assembled with position and angle control method.

Mode	Input	Output
LP_{01} (HE_{11})	94.3 %	94.3 %
LP_{02}	2.0 %	0.3 %
LP_{11}(o)	0.6 %	1.5 %
LP_{11}(e)	0.4 %	0.2 %



Amplitude Phase

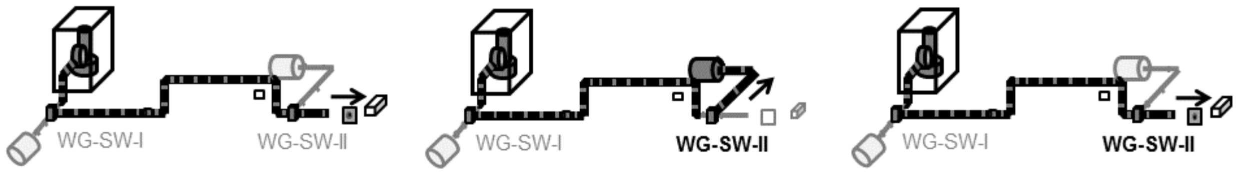
TL inlet



Amplitude Phase

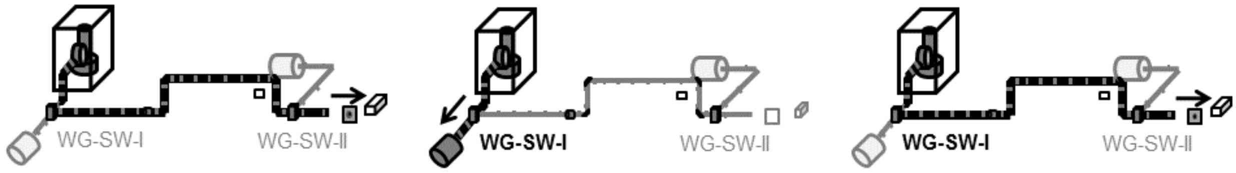
Long TL outlet

Figure 4. Retrieved RF field profile in the waveguide outlet after TL assembly.



(i) Profile measurement at long TL (Before operation) (ii) Long pulse operation on long TL (iii) Profile measurement at long TL end (After long TL operation)

(a) Long TL operation



(i) Profile measurement at long TL (Before operation) (ii) Long pulse operation on short TL (iii) Profile measurement at long TL end (After short TL operation)

(b) Short TL operation

Figure 5. Procedure of mode content measurement under effect of long pulse operation of TL.

The mode content at the outlet of the long TL was measured. The mode content at TL input and output is listed in Table 3. After 40 m transmission, LP_{01} mode purity was 93% where LP_{01} mode at 2 m distance from MOU was 94%.

Table 3. Mode contents in TL input and output.

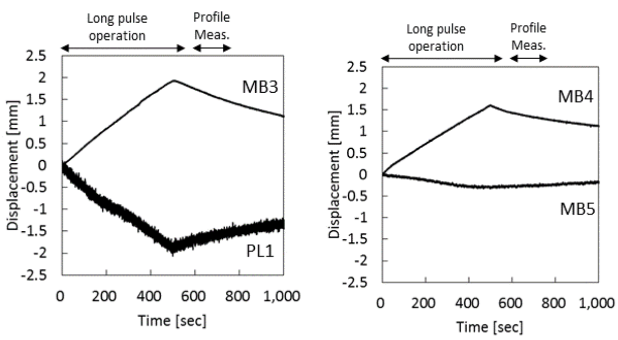
Mode	TL input (MOU output)	TL output (Long TL end)
LP_{01} (HE_{11})	94.4 %	93.1 %
LP_{02}	1.3 %	1.1 %
LP_{11}(o)	0.5 %	0.6 %
LP_{11}(e)	<0.1 %	1.3 %

4 Mode Conversion with Long-Pulse Operation

The mode conversion caused in TL test stand with high-power long-pulse operation was measured. As shown in Fig.1, TL included two waveguide switch and 3 vertical WG sections. Each vertical section was consisted from two miter bends and a short length waveguide piece. High power RF dummy loads were connected at the end of short TL and the branch section of long TL. The RF window was installed at the end of long TL and the radiated beam was applied for mode content measurement. The thermal imaging camera was utilized for mode profile measurement. The horizontal displacements of miter bends were measured using the laser displacement.

The measurement of TL test was carried out for both long and short TLs. Firstly the mode profile at the initial condition was measured at the end of long TL. The 170 GHz gyrotron provided 400 kW RF beam into TL for 500 s. RF power was delivered to the dummy load in branch section of the long TL. When the pulse was end, WG-SW-II immediately changed the RF direction to beam profile measurement section where the end of long TL. RF field profiles were measured within 50 - 250 s after the end of long-pulse operation. With decline of waveguide temperature, thermal expansion and TL deformation reduced and the TL system recover the initial condition. The history of measured displacements of miter bends were plotted on Fig. 6. This displacement was caused by thermal expansion of the straight section and this deformed the vertical waveguide section.

Next long-pulse operation with the same power / pulse duration was carried out for short TL. RF power was delivered to the terminal load of short TL. When the pulse was terminated, WG-SW-I immediately changed the RF direction for beam profile measurement as the same to long TL operation. Again beam profile was measured at long-TL end.



Vertical section 2 (PL1-MB3) Vertical section 3 (MB4-MB5)

Figure 6. History of miter bend's displacement during long pulse operation.

Figure 7 shows the retrieved field profile at the end of long TL for before the long pulse operation and after the long-pulse operation in long TL and short TL. The analysed mode content from retrieved beam profiles were listed in table 4. Analysis result of mode content showed that LP_{01} mode content was reduced by 7% at long TL operation and by 4% at short TL operation. On the other hand, LP_{11} mode in the transmission power was found to increase by 9% and 5% for long TL and short TL respectively. This indicated that the mode conversion in TL was increased by long pulse operation. The mode conversion from LP_{01} mode to LP_{11} mode could be caused by waveguide curvature of the deformed waveguide.

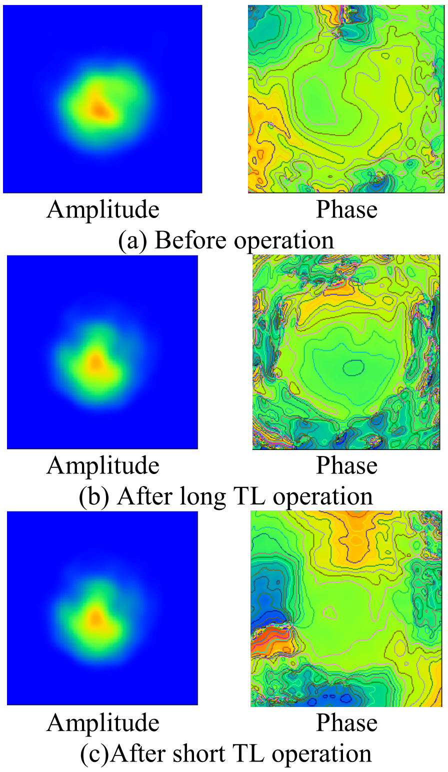


Figure 7. Retrieved RF field profile in the waveguide outlet before and after long/short TL high-power long-pulse operation.

Table 4. Mode content before and after the long/short TL high power long-pulse operation.

	(a) Before Operation	(b) Long TL Operation	(c) Short TL Operation
LP_{01} (HE_{11})	91 %	84 %	87 %
LP_{02}	1 %	2 %	1 %
LP_{11}(o)	1 %	10 %	6 %
LP_{11}(e)	4 %	1 %	2 %

The deformed vertical section causes mode conversion caused by namely S-bend structure as shown in Fig.8.[15] The structure of S-bend was described wit a plynomial equation according to ref.15,

$$y(z) = \frac{zD}{2L^3}\left(3L^2 - 4z^2\right) \quad (1)$$

Here y, z, D, and L are coordinate of displacement, axial coordinate, total displacement, and length of S-bend section. The mode conversion in S-bend was calculated as shown in Fig.9. Figure 10 shows the dependence of total mode conversion from LP_{01} mode on displacement of S-bend section.

Then the mode conversion in TL test stand during the long-pulse operation was calculated assuming S-bend structures at the vertical sections in TL and measured displacement at each section. The calculated mode conversion values for each TL section in the test stand under long pulse operation are listed in table 5.

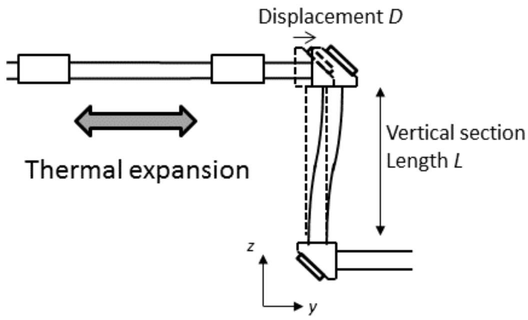


Figure 8. Thermal expansion and deformation of TL structure.

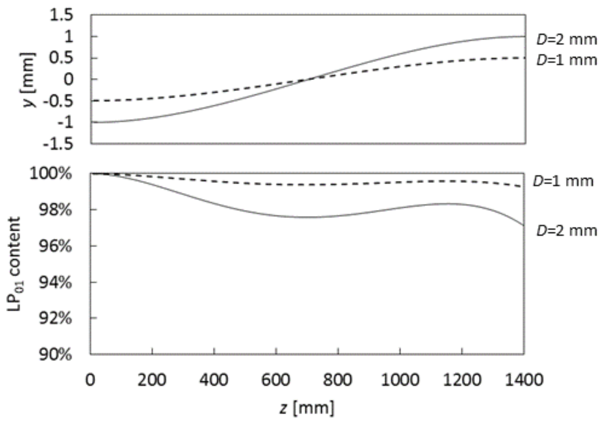


Figure 9. Structure of S-bend and calculated mode conversion. L=1400 mm / D=1,2 mm case was plotted.

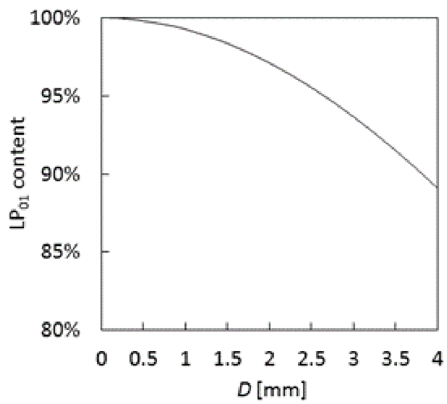


Figure 10. Dependence of mode conversion in S-bend structure on displacement of the section. L=1400 mm case.

Table 5. Length and measured deformation of the vertical section in TL test stand and estimated mode conversion value at each section.

Long TL operation

	L	*D*	Mode Conversion
MB1-MB2	1000 mm	0.7 mm	0.5 %
PL1-MB3	1400 mm	2.9 mm	6.0 %
MB4-MB5	1100 mm	1.6 mm	2.0 %
Total			8.5 %

Short TL operation

	L	*D*	Mode Conversion
MB1-MB2	1000 mm	2.3 mm	4.0 %
Total			4.0 %

Measured mode purity in TL changed significantly during the high-power long-pulse operation, although the JAEA TL test stand achieved 96% of transmission efficiency.[8] The transmission loss may not increase with thermal deformation of TL structure because mode conversion loss generates low mode number HOMs like LP_{11} mode which has low transmission loss in the waveguide. However the long-pulse operation affects the beam radiation characteristics from the TL outlet significantly and transmission loss in quasi-optical launchers may increase. Thereby it is necessary to reduce the thermal deformation of TL structure in ITER.

5 Summary

Alignment method with position and angle adjustment was proposed for TL assembly to reduce mode conversion loss in the straight section. Since periodic deflection of TL may cause mode conversion even if the deflection is small. After TL assembly with proposed method, LP_{01} mode content at end of the TL was 93% while 94% mode purity beam injection. To achieve required specification in ITER, alignment method for TL assembly is important.

Mode conversion caused by thermal deformation of TL due to high-power long-pulse operation was studied. Mode content after the long-pulse operation and TL deformation during long-pulse operation was measured. After 400kW/500s operation in long TL, LP_{01} mode purity at TL end was measured as 84% while mode purity before the operation was 91%. LP_{11}(o) mode was increased After the operation in the short TL, LP_{01} mode purity was 87%. Mode conversion was calculated S-bend structure with measured displacement of deformed TL section and mode conversion on long and short TL operation was estimated as 8.5% and 4% which showed good agreement with measured mode content.

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