Development of the Multi-Beam Transmission Line for DTT ECRH system

Saul Garavaglia[1*], *Alex* Bruschi[1], *Francesco* Fanale[2,3], *Gustavo* Granucci[1], *Alessandro* Moro[1], *Paola* Platania[1], *Afra* Romano[2,3], *Stefan* Schmuck[1], *Alessandro* Simonetto[1] and *Espedito* Vassallo[1]

[1]Institute for Plasma Science and Technology – CNR, via Cozzi 53, 20125 Milano, Italy
[2]ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, via Fermi 45, 00044 Frascati, Italy
[3]DTT S.C. a r.l., via Fermi 45, 00044 Frascati, Italy

Abstract. The DTT tokamak, whose construction is starting in Frascati (Italy), will be equipped with an ECRH system of 16 MW for the first operation phase and with a total of 32 gyrotrons (170 GHz, ≥ 1 MW, 100 s), organized in 4 clusters of 8 units each in the final design stage. To transmit this large number of power beams from the gyrotron hall to the torus hall building a Quasi-Optical (QO) approach has been chosen by a multi-beam transmission line (MBTL) similar to the one installed at W7-X Stellarator. This compact solution, mainly composed of mirrors in "square arrangement" shared by 8 different beams, minimizes the mode conversion losses. The single-beam QOTL is used to connect each gyrotron MOU output to a beam-combiner mirror unit and, after the MBTL, from a beam-splitter mirror unit to the ex-vessel and launchers sections located in the equatorial and upper ports of 4 DTT sectors. A novelty introduced is that the mirrors of the TLs are embodied in a vacuum enclosure, using metal gaskets, to avoid atmospheric absorption losses and microwave leaks. The TL, designed for up to 1.5 MW per single power beam, will have a total optical path length between 84 m and 138 m from the gyrotrons to the launchers. The main straight section will travel along an elevated corridor ~10 m above the ground level. The development of the optical design reflects the constraints due to existing buildings and expected neutron flux during plasma operation. In addition, the power throughput of at least 90% should be achieved.

1 Introduction

The Divertor Tokamak Test (DTT) is a superconducting device (B_T=6 T, I_P=5.5 MA, R_0=2.19 m, a=0.7 m, pulse duration of 100 s, 1 pulse per hour) under construction in ENEA Frascati (Rome, Italy) [1]. DTT will study suitable solutions for the power exhaust issue in conditions relevant for the future fusion device DEMO [2]. For this purpose, a key role is assigned to the additional heating systems; DTT will be equipped with ECRH, ICRH and NBI for a total power of 45 MW. The ECRH system will provide 16 MW for the first operation phase and a total of 32 gyrotrons (170 GHz, ≥ 1 MW, 100 s); a joint procurement with F4E for the first 16 gyrotrons is started and the acceptance of the first pre-series gyrotron is foreseen in the second half of 2023. The ECRH system is linked with several physics tasks including the core heating and MHD mode control [3]. The effective capability of the ECRH system to fulfil the requirements has been verified with the use of beam tracing GRAY [4, 5] considering the reference DTT Single-Null full power scenario [6].

The development strategy is based on the implementation of automatic operations, high reliability, high modularity and reduced maintenance. Existing and assessed technology (exploiting ITER and W7-X experience) is preferred according to the ambitious schedule for the first plasma in 2028. The architecture of the system (see Fig. 1) consists of 4 clusters, each one equipped with 8 gyrotrons. The gyrotron output Gaussian beams are transmitted by an evacuated Quasi-Optical (QO) single/multi-beam transmission line (SBTL/MBTL) towards two antennas, one upper and one equatorial, placed in the same DTT sector.

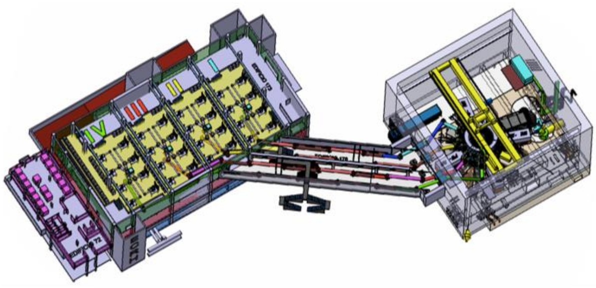

Fig. 1. 3D CAD model of ECRH building (left), THB (right) and the joining bridge (centre).

The ECRH building is organized on three different levels: the basement hosts the cooling system and the electrical substation, the ground level carries 16 gyrotrons High Voltage Power Supplies (HVPS)

* Corresponding author: saul.garavaglia@istp.cnr.it

groups, and the first level accommodates 4 gyrotron clusters. The 4 MBTLs run from the ECRH building to the Torus Hall Building (THB) over a bridge, penetrate the bioshield of the THB at 2.6 m above the equatorial plane of the machine and are connected to the upper and the equatorial ports of the tokamak sectors 12, 14, 16 and 18 dedicated to ECRH [7]. This paper reports the updated description and the solution adopted for the transmission line (TL) of the ECRH system, together with the wave propagation assessment to validate the model.

2 TL Conceptual design

The TL concept is based on the QO propagation of Gaussian beams at 170 GHz under vacuum, realized by a set of mirrors in a confocal arrangement. For the most part of the path, the TL exploits the multiple beam option with 8 TEM_{00} Gaussian beams, separated at the input plane, sharing a set of oversized parabolic focusing and flat mirrors, similar to the W7-X stellarator TL [8]. In order to minimise the transmission losses and arc risk, TL mirrors are proposed for the first time embodied in a vacuum enclosure using large metal seals. The design requirements are a target transmission efficiency of 90% and a power handling capability of 1.5 MW per single beam allowing any future power gyrotron upgrade. The design of the whole TL is a trade-off between the mirrors dimension (depending on the beam radius on the mirror surface) and the distance between two focusing mirrors. The main MBTL unit is composed by 4 identical dog-legs, including each a focusing mirror and a flat mirror at 90◦ reflections (Fig. 2).

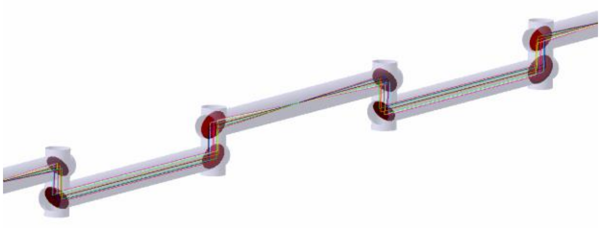

Fig. 2. 3D CAD model of MBTL basic concept, composed by 8 reflecting mirrors (4 focusing and 4 flat mirrors) with 90◦ reflections.

The focusing mirrors are in square configuration in order to compensate the aberrations due to the off-axis reflection of the beams [9]. The length of this TL section is chosen to cover the straight corridor (Fig. 3). The wave polarisation is selected at the input of each MBTL to minimise the ohmic losses due to mirror reflections. The TL is divided in three parts (Fig. 3): the first connects each gyrotron of one cluster to the combiner mirror at the geometrical centre of the cluster. The second part is the MBTL section that is from the combiner mirror of each cluster to the splitter mirror in the THB. In the last part the eight beams are divided into a bundle of six beams directed inside port 3 (equatorial) and two beams inside port 2 (upper), housing the Equatorial Antenna (EA) and the Upper Antenna (UA) respectively.

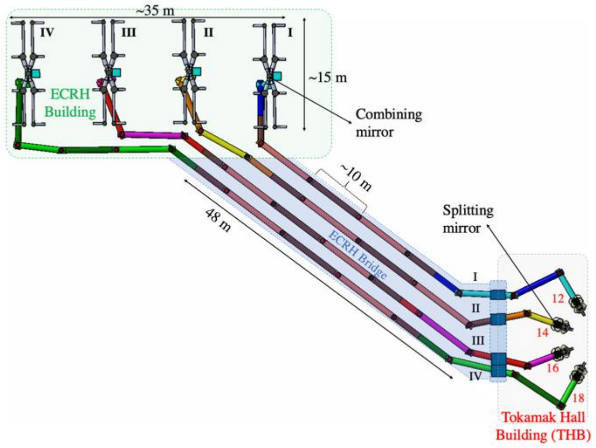

Fig. 3. Top view of TLs, including the SBTL in the ECRH building (top left), the MBTL along the bridge (centre) and the penetrations in the THB with the connections to the DTT dedicated sectors (bottom right).

2.1 Single-Beam TL in ECRH building

The design of the single-beam transmission line (SBTL) in the ECRH building considers several requirements including the minimisation of the space occupied by the 4 clusters, the minimization of the number and the types of required mirrors, the choice of a beam size small enough to reduce the vacuum enclosure and the number of vacuum components. For these reasons, the 8 gyrotrons of each cluster are arranged into 2 rows of 4 items each, with a 5 m distance between two gyrotrons to avoid mutual magnetic disturbance due to the superconducting magnets (Fig. 4). The 8 output beams are refocussed and collected together in the centre of the cluster on a combining mirror achieving a two axes symmetric cluster arrangement. The created bundle of beams is then reflected downwards to propagate inside the MBTL.

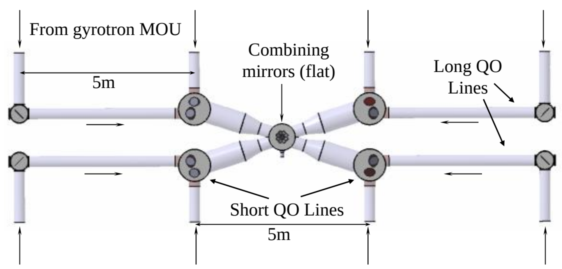

Fig. 4. Top view of the 3D CAD model of SBTL arrangement for one cluster in the ECRH building.

This geometry reduces the number of the matching optics types to one for the 4 nearby gyrotrons (short) and one for the remaining gyrotrons (long), maximising the modularity. Each path is composed by one (short) or two (long) single focusing mirrors respectively and one plane polarising mirror to set the favourable input polarisation for the MBTL to minimise the ohmic losses. For each line, the last mirror before the combining mirror is movable to reflect the incident beam towards the combining mirror or the rotable plane mirror placed in the geometrical centre of the cluster above the combining mirror. This rotable mirror directs the beams, one at a time, toward a RF load close to the combining unit through a second fixed focusing mirror located below it as shown in Fig. 5.

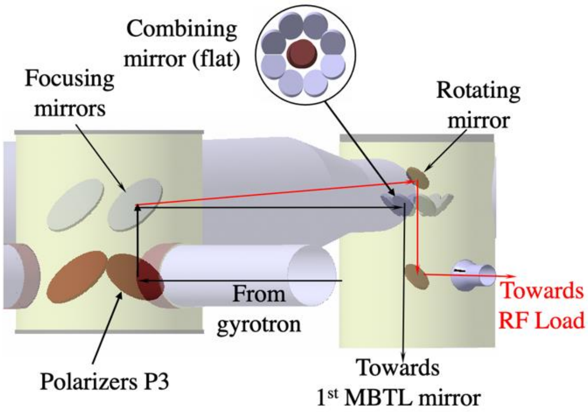

Fig. 5. Detail of the connection between SBTL and RF load. The beam coming from the gyrotron can be tilted by a focusing mirror to reach, on top in the centre of the combining mirror, the rotating plane mirror. This mirror is designed to redirect the beam vertically down where the fixed mirror reshapes the beam and directs it into the load (red arrow).

2.2 Multi-Beam TL

The MBTL consists of a straight section running along the corridor. At its ends, the connections have been realized in telescopic arrangement to reach the combining mirror under the gyrotrons cluster centres on one side and the splitting mirror in front of the dedicated ECRH tokamak sectors on the other side (Fig. 3). The 8 beams are arranged on the vertices of an ideal octagon (Fig. 5 top) and start (and end) parallel to run in the MBTL spatially separated. They propagate alternatively crossing or parallel to each other between two focusing mirrors on which they have maximum size and minimum power density. The MBTL design considered several constraints including the positions of the pillars and walls of existing buildings, the minimum clearance to be left around the TLs for maintenance, and the use of the same ex-vessel structure in front of the DTT sector. A particular attention has been dedicated to the bio-shield penetration in the THB to limit the neutron streaming in accordance with the restriction rules [10]. In the corridor, the mirror units are positioned at ~10 m distance whereas outside the corridor the distance between focusing mirrors has been reduced and adapted depending on the various paths. Only five types of mirrors with four different dimensions are necessary for the four clusters.

2.3 Single-Beam TL in THB

The last section of the TL matches the beams coming from the MBTL with two types of antennas: two beams are redirected to the upper antenna in port 2 and six beams to the equatorial antenna in port 3. The ex-vessel single-beam optics in the THB is the same for all 4 clusters (Fig. 6). The splitting mirror is located in front of the corresponding tokamak sector at about half height between port 2 and port 3. Only one focusing mirror is included to match each single beam at the splitting mirror to the one at the input of waveguide (WG) before the launchers. Two polarising mirrors in z-shape optical path are also included in order to optimise the coupling between the launched wave and the plasma in real time. Three optics configurations have been found: one for the two beams launched from port 2 (yellow, Fig. 6 left), one for the three beams of the top launchers (green) and one of the bottom launchers of port 3 (magenta).

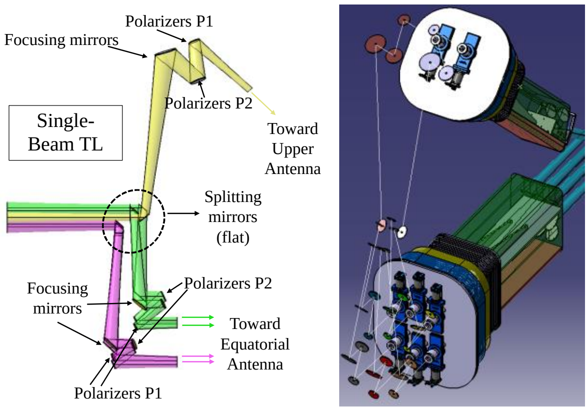

Fig. 6. Left: SBTL design in the THB. Right: upper and equatorial launchers and ex-vessel transmission lines.

2.4 Mirrors

The design criteria of the MBTL mirrors are driven by the lowest temperature increase of the reflectors during the RF discharge and the minimum surface deformation. The latter seems to depend critically on the temperature inhomogeneity due to the heat load. For this reason, a set of different combinations of materials and cooling solutions has been evaluated. The present reference is a copper body of 20 mm thickness on top of which a planar cooling channel layer is obtained, and a cover copper layer of a minimum thickness of 4 mm. The mirror is water cooled through a double spiral circuit with semi-circular channels section. The mirrors have an elliptical shape and the dimensions, sized to allow the reflection of 99.97% of power, are between ~1.1 × 0.8 m for the MBTL and ~0.35 × 0.25 m for the SBTL. Table 1 reports the number of mirrors for one representative beam of each of the 4 TLs, the total number of mirrors for the MBTL, the path length (considering short and long lines in the SBTL section) and the volume.

Table 1. Number of mirrors, length and volume of TLs.

TL	MBTL mirrors	Total mirrors	Length [m]	Volume [m^3]
I	17	77	84-90	68
II	17	77	89-95	71
III	21	81	104-110	78
IV	25	85	130-137.5	87

2.5 Vacuum system

One of the novelties of the system is the evacuation of the QOTL. The vacuum envelope is a cylindrical chamber that contains the mirrors and the related structures at ~1 mPa of target pressure. The material of the enclosure is stainless steel (a lighter option in Aluminium is under evaluation) with a diameter of 800 mm (300 mm) and thickness of 6 mm (3 mm) for the MBTL (SBTL). A preliminary design of the pumping system was carried out as a function of volume to be pumped out and of surface of the vacuum chamber. Two pumping units are planned at the ends of each TL near the gyrotron clusters and close to the THB in the corridor. The DTT vessel volume is ~100 m^3 at a pressure of ~10^{-2}-10^{-3} mPa (~10 mPa during the discharge). At present, the connection between the vacuum vessel and TL will be regulated only by an all-metal gate valves without the presence of a diamond windows as used in other tokamaks. This valve is normally closed and is opened only during the ECRH pulse. An analysis of the vacuum system dynamics [11] revealed the need to drastically reduce the conductance between the TL and vacuum vessel not to compromise plasma operations. In fact, at the simultaneous aperture of the 32 gate valves, a gas flow from the tokamak of the same order of the gas injected in the DTT vacuum vessel to sustain the plasma density is expected. For this reason, a section of corrugated WG 63.5 mm diameter, ~1.5 m length has been included in the beam path at the transition between the SBTL enclosure and the launcher internal part to marginalise the impact on the tokamak gas puffing. However due to the uncertainties on the parameters used in the simulations, the variability of DTT scenarios and different operating modes of the ECRH system, a back-up solution with the later use of a diamond windows will remain possible. The optical design has consequently been made compatible for the matching with the WG insertion.

2.6 Propagation assessment

In order to investigate the TL design model, evaluations of the propagating power density and losses have been performed with the use of GRASP [12]. After the four TLs have been modelled in the GRASP environment, the beam propagation along the TL has been simulated. The following results refer to the ideal case, obtained considering the TL optically aligned and undeformed mirror surfaces. The coupling losses are low as expected in the modular straight part of the MBTL (0.16%) and higher outside (between 2% and 2.35% depending on the TL). The spillover is of the order of 0.05% for all the TLs due to the mirrors size choice which means that the radiated power not intercepted by the mirrors and enclosed in the vacuum chamber is of the order of a few kW per line. The ohmic losses, depending on the polarisation selected at the input, range between 2.2% and 4.0% including a factor of 1.3 for the mirror's roughness. The total loss is estimated to be between 4.7% and 6.3% for the shortest/longest TL, when SBTL mirrors are included in the analysis. The additional coupling loss due to the transition of WG (TEM_{00}-HE_{11}-TEM_{00}) in the optical path introduces an extra maximum contribution of 4%, which can be reduced either by tuning the waveguide length and beam waist or by adding an optimized HE_{11}-TEM_{00} taper at least on one end. To reach a more realistic and all-inclusive estimate of losses, two analyses are still ongoing. The first is the inclusion in the GRASP model of the deformation effects of the mirrors surface due to the thermal load that can introduce effects on the beam alignment. The second analysis calculates the required tolerances in the alignment of the mirrors with a software based on Monte Carlo analysis of the geometric optics [13].

3 Conclusion

Progress in the development of the MB TL of DTT's ECRH system is presented. The layout of the system has been consolidated with a modular architecture based on clusters. The design of the Single/Multi-Beam QO TL is extensively studied including the novel solution to evacuate the TL. The next efforts will be dedicated to complete and validate the TL conceptual design including the deformation effects in the electromagnetic analysis with an improved mirror cooling to complete the evaluation of the impact on the losses.

References

1. R. Martone et al., ISBN 978-88-8286-378-4 (2019)
2. R. Ambrosino et al., Fus. Eng. and Des. **167**, (2021) 112330
3. G. Granucci et al., Fusion Eng. Des. **122** (2017) 349–355
4. D. Farina et al., Fusion Sci. Tech. **52**, 154 (2007)
5. B. Baiocchi et al., this conference (2022)
6. I. Casiraghi et al., Nucl. Fusion **61** (2021) 116068
7. S. Garavaglia et al., Fusion Eng. Des. **168 (**2021) 112678
8. V. Erckmann et al., Fusion Sci. Technol. **52** (2007) 291–312.
9. L. Empacher, W. Kasparek, IEEE Trans Antennas Propag. **49** (2001) 483–493
10. A. Colangeli et al., Fus. Eng. and Des. **171**, (2021)112690
11. S. Garavaglia et al., Journal of Vacuum Science and Tech. B *under publication*
12. GRASP, Technical Description, TICRA (www.ticra.com)

13. A. Simonetto, ISTP internal report FP20/05 (rev. Apr. 2022)