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Conceptual design of the DTT ECRH quasi-optical transmission line

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ABSTRACT

The Divertor Tokamak Test (DTT) facility is being realised in Frascati, Italy for the study of the power exhaust issues in view of DEMO tokamak. A multi-MW Electron Cyclotron Resonance Heating (ECRH) system is foreseen with a first set of 16 gyrotrons at 1 MW and 170 GHz available for the first stage of operation; additional 16 gyrotrons with power from 1 MW to 1.2 MW are foreseen in a later stage for a total of up to 33.6 MW of ECRH at plasma. ECRH system itself is part of the 45 MW of external additional heating coupled to the plasma, provided also by Ion Cyclotron Resonance Heating and Neutral Beam Injection. The Transmission Line (TL) is fully quasi-optical, between 84 m and 138 m long and will transfer power up to 1.5 MW per beam from the building hosting the ECRH sources to the Torus Hall. The main section runs in a straight elevated corridor at a few meters above the ground level. In order to have low power losses and a simpler and manageable system, the long TL run is made by four quasi-optical Multi-Beam (MB) lines each transmitting 8 beams via shared mirrors, similar to the W7-X Stellarator TL. The system is thus organised in "clusters" each one made of the 8 gyrotron sources and the respective transmission line and launchers. Avoidance of losses in air and microwave leaks is assured by a vacuum enclosure of the whole line with the use of metallic gaskets. Single-Beam (SB) transmission lines are foreseen at the beginning and end of the MB line, to cover the distance from the gyrotron to a beam-combining mirror and from a splitting mirror to the launcher. The optical design has to cope with space constraints in the building and inherent conversion losses at the reflection on metallic mirrors, whose number was minimised. First evaluations with the electromagnetic modeling tool GRASP and first concepts for the MB mirror cooling are reported.

1. Introduction

The Divertor Tokamak Test (DTT) facility [1–5] for the study of the power exhaust issues in view of DEMO tokamak [6] is being realised in Frascati (Italy). The aim is to test the power handling issues and in particular the power exhaust through different divertor configurations and design concepts at power levels that are relevant for the future fusion devices. For this task, a high power amount must be injected into the plasma, so that the power density onto the divertor and other characteristics (particle energy, larmor radius, intermittency) will be similar to those expected in DEMO. A mix of additional heating power systems (up to 45 MW in total) has then been selected [7], including Neutral Beam Injection [8] and Ion Cyclotron Resonant Heating [9].

The main contribution to the power (up to 33.6 MW) shall be provided by the Electron Cyclotron Resonance Heating (ECRH) system [10], for which a dedicated building is assigned (Fig. 1). One of the main requirements for the location of the ECRH sources is the maximum external magnetic field tolerable by the gyrotrons. This sets the minimum distance from the tokamak, that is respected by the ECRH building. In order to have the minimum transmission losses, shortening the distance (vertically and horizontally) from the gyrotron hall to the tokamak, a long corridor suspended by pillars has been foreseen, large enough to accomodate the Transmission Lines (TL).

Given the required power and the steps of installation in time, it is natural to organize the sources in four "clusters" each one made of 8 gyrotron sources and the respective transmission line sections and

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launchers. The TL will consist of four 8-beams bundles guided by mirrors (forming four quasi-optical TLs) and enclosed by a set of evacuated pipes extending to the end of the corridor. Each of the four lines will penetrate the Tokamak Hall Building (THB) through holes in the bio-shield and will be directed in the same enclosures to four even sectors (12, 14, 16, 18) of the DTT, leaving the sector in between free for remote handling activities. Near to the launchers the beam bundles are split in single beams, two of which will be directed to the upper antenna (in port 2) and six to the equatorial antenna (in port 3). Before entering the antenna each beam is focused by a shaping mirror, passing through a universal polarizer made of two corrugated mirrors, and is coupled into the antenna.

2. Quasi-optical transmission line concept

While many ECRH systems in present fusion devices use corrugated waveguides for power transmission from the gyrotron to the launcher, the DTT TL concept is fully based on the propagation of Gaussian beams at 170 GHz under vacuum, realized by a set of mirrors, some focusing and some plane, in a specific arrangement. The DTT TL for each cluster is composed by Single-Beam TL (SBTL) from the sources to a so-called combining mirror where 8 beams at a time are combined together in one bundle and propagated by a Multi-Beam TL (MBTL) with bigger focusing and plane mirrors in a dog-leg path up to the DTT THB. Here a cluster will be connected to either the DTT sector 12, 14, 16 or 18, where ECRH antennas are located.

2.1. Single beam transmission line (SBTL) design

The microwave power produced by each gyrotron is shaped in a Gaussian distribution with plane wavefront at their output by a Matching Optics Unit (MOU) provided by the gyrotron manufacturer. From the MOU the Gaussian beam power distribution and its propagation (beam expansion in free space) is modeled with standard formulas of quasi-optical (QO) theory [11]. In order to transmit individual beams to a unique location where they can be bundled together, the cluster is organized in a symmetric modular arrangement with 2 rows of 4 gyrotrons placed with the output beams facing each other, with the combining mirror placed in the center of the two axes of symmetry (Fig. 2).

This symmetry allows to keep maximum modularity, designing a matching optics of just two types, one for the gyrotrons closer to the combiner (short QO lines, with the use of one single focusing mirror and one plane mirror) and one for the gyrotrons far from the combiner (long QO lines, with the use of two focusing mirrors and one plane mirror) as shown in Fig. 2.

Optionally, the plane mirrors can be replaced by fixed polarizers to optimize polarization at the beginning of the MBTL in order to minimize the ohmic losses due to reflections on the mirrors.

The combiner mirror consists of plane mirrors placed in an octagonal shape. These mirrors redirect the incident eight beams downwards towards the first mirror of the MBTL. To allow the bundling, the combiner mirror centers (and axes) must be separated by a distance of at least 4 w_{MBTL}, where w_{MBTL} is the chosen waist size (~25 mm) of the Gaussian beam at the combiner position (Fig. 3). This gives the radius of the circle of the beam centers $r_B = 1.306*4w_{MBTL}$ (1.306 is the ratio between the circumradius and the side of the octagon). The radial dimension of the mirror (projection on the plane x-y at constant height as in Fig. 3) is then:

$$r_M = r_B + 2w_M = 1.306*4w_{MBTL} + 2w_{MBTL}.$$

The actual position of the x-y axes in Fig. 3 with respect to the cluster geometry is not free. The axes are rotated by a different angle for each MBTL, in order to compensate the different rotation of the octagon in the MBTL path.

In fact, it is convenient to have a fixed arrangement of the beams at the end for all the MBTL, with the y axis in the vertical direction at the splitter position.

The small differences between the paths from the last mirror of the SBTL to the combiner mirrors will introduce a small shift of the beam waist position, that can be compensated with small variations in the optics.

The matching of the beam waist, present at the gyrotron MOU output, to the one required at the combiner is the main objective of the SBTL. The focal lengths and mirror positions and sizes were adjusted with the aim to:

- Keep the space in front of the gyrotrons clear enough for maintenance and alignment procedures
- Minimize the number of mirrors required, in order to minimize losses.
- Keep the beam size small enough for minimizing the size of the vacuum enclosures.
- Minimize the number of vacuum components with the inclusion of boxes housing multiple mirrors.

The mirror positions and the beam optics have been studied also to include in the design a single QO line departing from the combiner enclosure and feeding a single Radio-Frequency (RF) load to be used for conditioning and power measurements of all the gyrotrons in a cluster. This required a specific placement of the last mirrors of the SBTL, in order to keep the same distance to the geometrical center of the

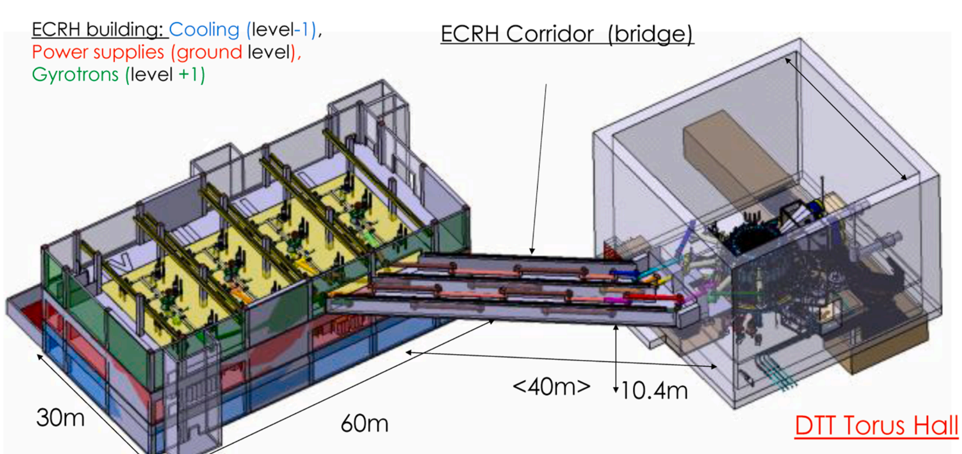

Fig. 1. Top view of the ECRH building (left) and DTT Torus Hall (right) joint by a corridor with the MBTL.

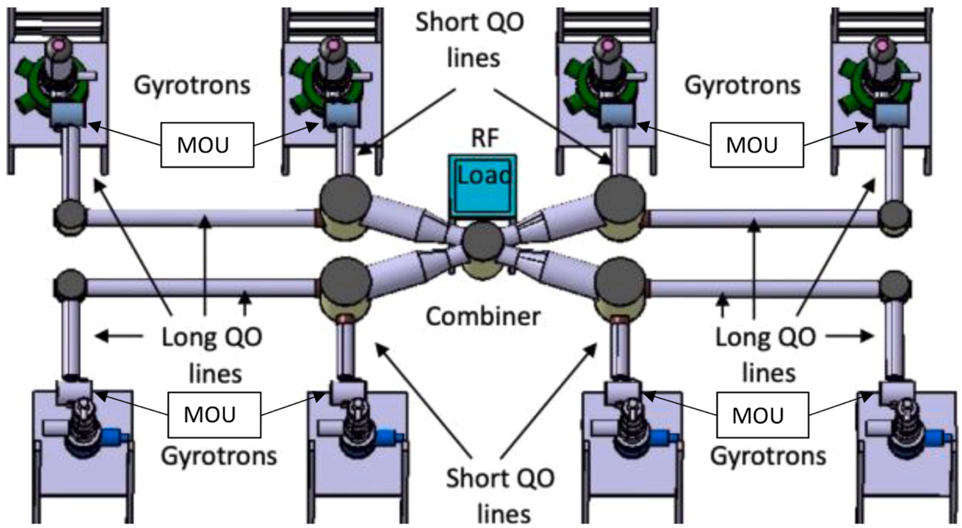

Fig. 2. View of the gyrotron arrangement of one cluster in the ECRH building and of the single-beam transmission lines.

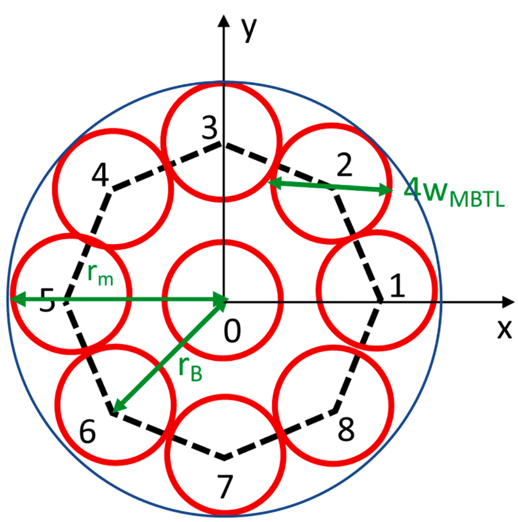

Fig. 3. . Arrangement of the 8 beams at the entrance of the MBTL at the combiner placed in the ECRH Building. A central beam is sketched for reference only.

combiner unit.

The final length chosen and the mirror focal lengths are shown in Fig. 4 where MM1 and MM2 are the mirrors of the long QO line and MM3 is the one of the short QO line. Mirror dimensions are around 350 × 250 mm.

2.2. High-power load placement in the ECRH building

Two RF loads for each cluster will be procured. Each load must be compatible with operations under high-vacuum, to absorb and measure absolutely the power delivered by the input Gaussian beam with high precision, during both short and long gyrotron pulses. The back-reflections of the load towards the TL must be low enough for compatibility with operations with the DTT gyrotrons, as well with precise power measurements, both performable without arcing or damages in the long term. The loads will be used in different positions: temporarily one will be installed close to each gyrotron after delivery for the on-site commissioning of the sources, and finally placed in a fixed position at the beginning of the MBTL, close to the combiner, for conditioning and testing of the commissioned gyrotrons and the SBTLs. A second load is foreseen at the end of the MBTL, close to the splitter, for conditioning and testing of the gyrotrons and the complete TL.

After gyrotron delivery, the load is requested to measure gyrotron power at the output of the gyrotron MOU. The RF load position in-line with the MOU can be used only when no elements of the SBTL of the specific gyrotron have been mounted, unless a very short RF load were available (see Fig. 5, Left). Existing RF loads are too large for that. For a normal-sized load, the position shown in the center of Fig. 5 has been studied, implying the need of an additional deflecting mirror. In this case, a position in between two gyrotrons as shown in the right of Fig. 5 is preferable and taken as reference.

The mirror focal length should be defined on the basis of the final beam (waist) size at the MOU and the RF Load agreed during the load procurement.

For routinely gyrotron conditioning or testing, a single RF load for one cluster will be installed in order to be connected, when needed, to the gyrotron of interest by switching the specific beam into the load. The optimal final placement of the RF Load in the gyrotron hall is close to the combining mirrors, where all the beams are close to each other. A placement at one side of the box housing the combiner was chosen, as in Fig. 2.

A specific design of a two-mirror line was performed for the use of the load with multiple gyrotrons (one at a time). The switching is obtained by a tilt of the last mirror of each SBTL directing the beams away from the combining mirror onto a plane mirror placed at the center of the combiner assembly (Fig. 6). The plane mirror is capable to rotate on a vertical axis and, provided all beams are incident with the same angle with respect to the horizontal plane, can deflect the beam downwards on a specific single vertical axis. This is possible by choosing for the last mirrors of the SBTL equal altitude and equal distance with respect to the rotating mirror, but it implied a redesign of the SBTL optics made for allowing the compatibility with this requirement. On this axis a concave ellipsoidal mirror will deviate the beam horizontally towards the RF load and reproduce a specific image of the input beam with dimensions compatible with the ones that are requested for the load input.

On the left side of Fig. 6 the SBTL mirrors to be tilted are shown, while in the center, on top of the combiner assembly, the rotating plane mirror is designed to redirect the beam vertically downwards on the fixed mirror that reflects it into the load.

2.3. Multi beam transmission line basic concept

In order to have low power losses and a simpler and manageable system, the long TL run is made by four QO MB lines each transmitting 8

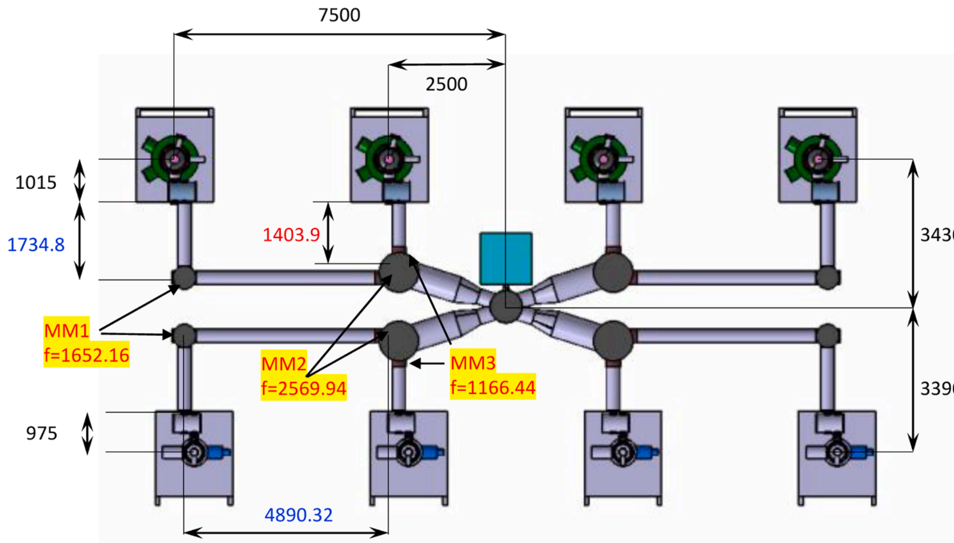

Fig. 4. Distances and focal lengths chosen for the single-beam transmission lines (in mm units).

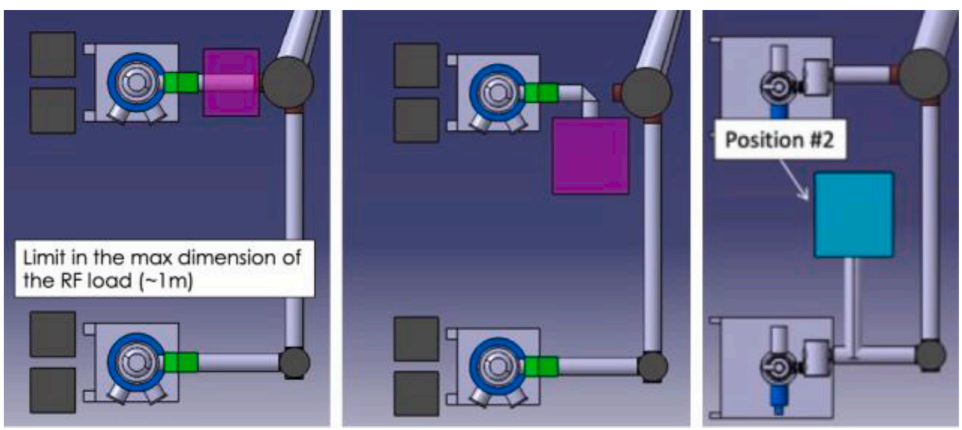

Fig. 5. Left: Placement of the RF Load in front of the gyrotron MOU (in green). Center: placement close to the MOU with a short bend (mirror). Right: preferred placement of the RF Load in between two gyrotrons (chosen option).

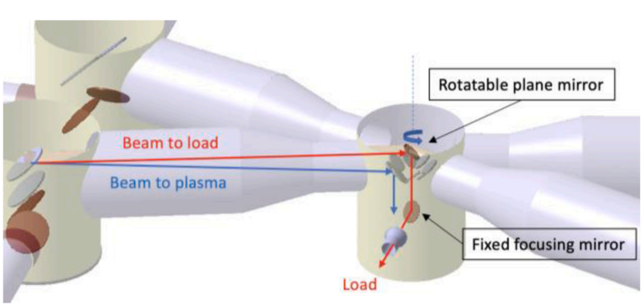

Fig. 6. The SBTL mirror at left is tilted to reach the rotating plane mirror, on top of the combiner assembly. This redirects the beam vertically down to a fixed shaping mirror and into the load.

beams via shared mirrors, similar to the W7-X Stellarator TL [12]. Each 8-beam bundle is guided by mirrors at specific distances and enclosed by a set of pipes extending to the end of the corridor, connecting to the TL section inside the THB through the holes in the bio-shield.

The MBTL concept is based on the Gaussian beam transmission with minimum distortions. This is realized by a set of mirrors, some focusing and some plane, in a confocal arrangement, capable to transmit a set of Gaussian beams properly spaced on the same mirror, thus minimizing the number of mirrors and the mirror area required for the TL. The concept has been used for the TL of W7-X (in air) and has been demonstrated to transmit power with minimal losses, provided a compensation of single-reflection beam deformations (aberrations introduced by the off-axis reflection of mirrors, see [13]) is effective. This occurs for specific arrangements of sets of four concave mirrors. This motivated the choice of using the rectilinear section of the corridor to host the long run of the TL with the specific (auto-compensating) confocal arrangement, using a set of four parabolic mirrors and four planar mirrors to obtain a so-called “square” configuration in [14].

The choice of parabolic shape for the mirror surface is justified by the simplicity of modeling the beam trajectories that only in this case have parallel and crossing beam axes. Another reason is that the results of the model described below confirmed that the performances of the paraboloid are comparable, if not better, than other shapes, as for example the elliptical paraboloid.

The design strategy of the MBTL is a trade-off between the mirrors dimension (depending on the beam radius on the mirror surface) and the distance between two focusing mirrors. This motivated the choice of the beam minimum waists for clusters 1 and 3 of 27.9 mm on the parallel beam section and the focal lengths of 5.05 m of the mirrors in the main MBTL. For the lines of cluster 2 and 4 the values are 31.5 mm and 5.7 m respectively. They were chosen to provide a manageable size of focusing mirrors (1076 × 760 mm) and a sufficiently long run to cover the corridor length for all the clusters.

In the corridor, mirror units are placed at about 10 m distance, whose enclosures are connected by cylindrical tubes under vacuum (in order to avoid losses in air). The beams propagate alternatively crossing or parallel to each other between two focusing mirrors on which they are separated, with the benefit of decreasing the power density on the mirrors, where each beam has the maximum size. This part of the TL has been modeled initially with a "reduced" model in the electromagnetic software GRASP [15], in order to have a first evaluation of the spillover and the coupling losses in the ideal case. The analyzed model is shown in Fig. 7 (top). The beams can only be separated when they are parallel and at a distance equal to the mirror focal length, being superimposed in all other positions along the line. The model initially considered parallel beams at both ends, like in W7-X [14] (Configuration 1).

2.4. Multi beam transmission line extended concept

Due to the distance of the gyrotrons and the launchers from the corridor, an extension of the main TL at both ends is preferably realised with other MBTL sections, but preferably with smaller and more manageable size of the mirrors and length of the sections, required for easing the reach of the cluster center and of the DTT sector reserved to the launcher and also the passage through the bio-shield wall. The optimal reduction of both mirror size and section length cannot be obtained conveniently with a transition to a different MBTL focal length at the place where the beams are parallel, since in that case the distance of beam axes would not be reduced.

As an alternative idea for matching the additional sections, the transition from the main line to the additional runs is made with the beams at both ends of the main line crossing instead of parallel. This would result in a "magnifying telescope" arrangement (confocal with two different focal lengths), reducing focal lengths, beam size and distance between focusing mirrors at the same time. A sketch of the main line in Configuration 2 with the transition to a MBTL with a different mirror size, focal length and beam size (all scaled by the same factor) is shown in Fig. 7 (bottom).

A study was performed in order to verify that the different concept for the main line, with crossing beams at the main line ends (Configuration 2) instead of parallel beams as in W7-X (Configuration 1) was not degrading the main line performances.

The study of the two configurations performed with GRASP [15] and parabolic mirrors confirmed the very low coupling losses of 0.16% for the straight path without a degradation for the Configuration 2.

The concept of W7-X TL has then been extended, adding, at the two extremes of the main MBTL, additional MB mirrors to connect the line to the gyrotrons and to reach the launchers. This allowed the use of the ideal beam size in the long run and of a manageable beam size and mirror distances at both ends of the MBTL.

The extensions in the initial and final parts of the TL are realised by necessity with mirror dog-legs bending the path in different directions. Being the resulting trajectory no more planar, the compensation of aberrations in the lines out of the main straight MBTL in the corridor is not ideal, and the coupling losses are expected higher.

The layout was adjusted several times in order to adapt the line to the position of the clusters, to the passage through the bio-shield, to keep a small number of different focal lengths (three) and to reduce the number of mirror types. Five mirror types with dimensions between 650 × 920 mm and 1076 × 760 mm have been used. Calculations with GRASP for the multi-beam sections of the clusters C1 (shorter TL) and C4 (longer TL) give coupling losses of 2% and 2.35%, mainly due to small variations of the final beam size and to astigmatism (Fig. 8). The E-field pattern computed with GRASP on a surface perpendicular to the beam has been analyzed in terms of mean values and moments of the $|E|^2$ distribution and of the far-field distribution, following the treatment found in [16]. With this method, the parameters of the best astigmatic Gaussian beam coupled to the field pattern can be inferred. For cluster C1 the inferred optimal beams couple 99.7% of the launched power in our case, with waists positions and sizes close to the designed ones, despite not identical. The coupling losses could then be reduced ideally to 0.3% designing the last mirrors such to match the found optimal beams to the launcher.

Due to the size of the mirrors the spill-over losses are very low, of the order of 0.05%, while overall ohmic losses, depending on polarization chosen at the input (combiner) can be lower than 2.2%.

Real losses must account for possible deformations of the MB mirrors due to the surface heat load caused by ohmic losses during long pulse operation (see [17,18]): a study of the MB mirrors and their cooling has

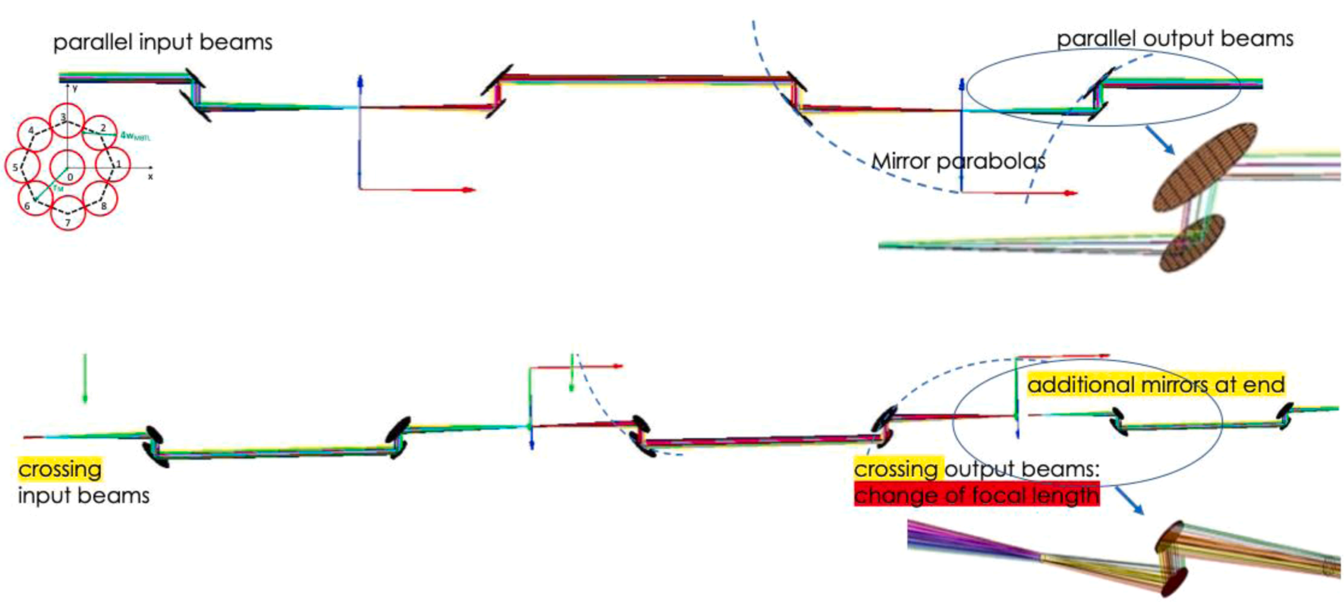

Fig. 7. Top: Simplified model in GRASP [15] of a possible optics for the main line in the corridor, with alternatively crossing and parallel beam axes in an octagon arrangement (when parallel), and the origin of the parabolas describing the mirror surfaces. Bottom: variant of the above setup with crossing beams at the sides of the main transmission line: on the right the connection with a downscaled MBTL is implemented at the crossing. In the real line the connection with downscaled MBTLs is done at both sides.

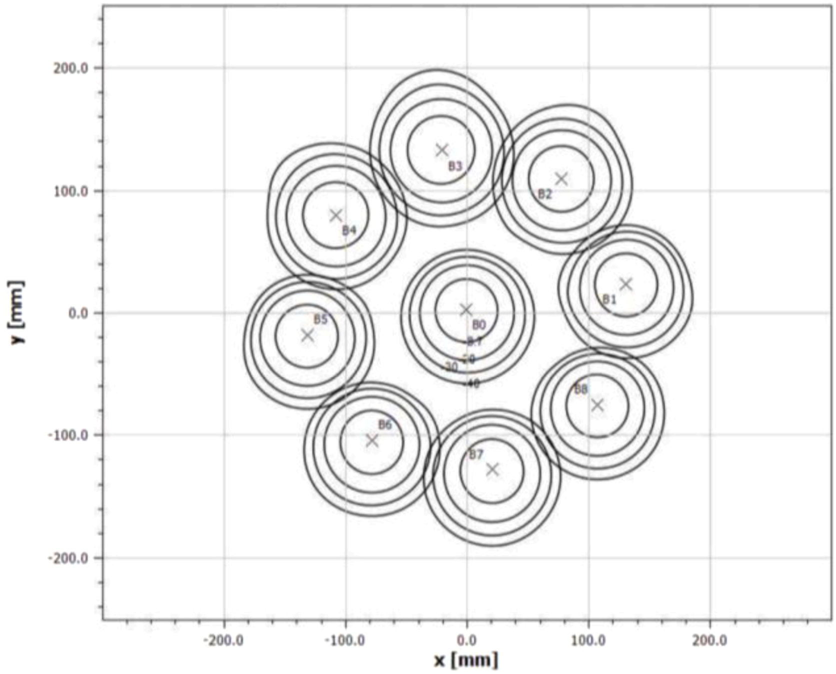

Fig. 8. Contour plots for the beams at the end of the MBTL for ideal input beams (contours at −8.7, −20, −30, −40 dB, the central beam is shown for reference only).

been performed (see next section), and a straight line including deformed surfaces was modeled in GRASP to evaluate the effects of deformations on beam coupling losses.

3. Design of mirrors for the MBTL

The design of the MB mirror cooling layout [19] initially considered was a circular channel following the incidence points of the beams on the surface of the mirror and different material combinations, then in a later stage a single spiral extending from the center to the periphery.

The maximum temperature reached during long pulses appeared not critical, being in an acceptable range even with a single spiral cooling circuit. The critical aspect of the cooling are the deformations induced by temperature inhomogeneity, not negligible for the beam propagation. The ohmic heat load deposited by the bundle of beams in fact is highly non-uniform (see Fig. 9).

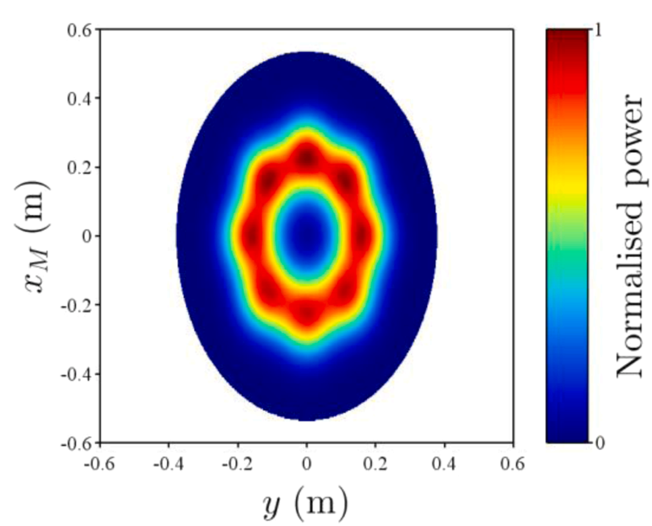

Fig. 9. Thermal load on the parabolic mirror, normalised to the maximum (143 kW/m^2).

In Fig. 9 the power is 1.5 MW for each beam and absorption is for copper, worst case polarization and roughness factor 1.3 [20]. The thermal analyses were performed with cooling rate of 20 l/min in a channel with section of 0.785 cm^2 (flow velocity 4.2 m/s, heat transfer coefficient Hc~18,000 $W/m^2/K$). The first to be tested was an aluminum mirror with a copper plate on the back including a circular channel. The structural analysis performed at a specific time (when the mirror reached the highest temperature during the pulse) showed a large deformation with a curvature radius of less than 100 m. The change of the materials to copper (surface, >5 mm thick) and steel (back, 25 mm thick) did not reduce the deformation curvature. A change to a full copper mirror increased the radius of curvature of the deformation above 240 m. With the deformation resulting from this thermal analysis, the GRASP model of the straight line of 8 mirrors described above has been run.

The analysis was performed just modifying the parabolic surfaces with the introduction of the expected surface deformations, neglecting the deformation of the planar mirrors. The high level of coupling losses between input and output Gaussian beams triggered a revision of the cooling system for the parabolic mirrors. A new design of the cooling layout has been considered, with the aim of subtracting heat in the region with the maximum load and heat the outer region of the mirror, where the fraction of absorbed power density due to Ohmic losses is several orders of magnitude lower than the central region. The new design consists of two spirals starting from a common inlet placed on the radius of maximum power deposition and revolving with opposite flows: one to the mirror center, the other toward the mirror periphery. Two different outlets are provided, and the flow is balanced with a variation of the diameter of the two channels (inner 12 mm and outer 15 mm). Cross-sections of the parabolic mirror are shown in Figs. 10 and 11. The mirror is in copper and has an elliptical contour with a dimension of 1076 × 760 mm and weight of 132 kg; the flow rate is 21 l/min with inlet temperature 30 °C. The maximum and minimum mirror temperatures reached during a pulse of 100 s are shown in Fig. 12.

The temperature distribution on the mirror surface after 100 s is shown in Fig. 13: this layout caused a reduction of the mirror deformations (max. deformation =0.14 mm, minimum curvature radius greater than 1000 m.) and, as confirmed by the calculations with GRASP

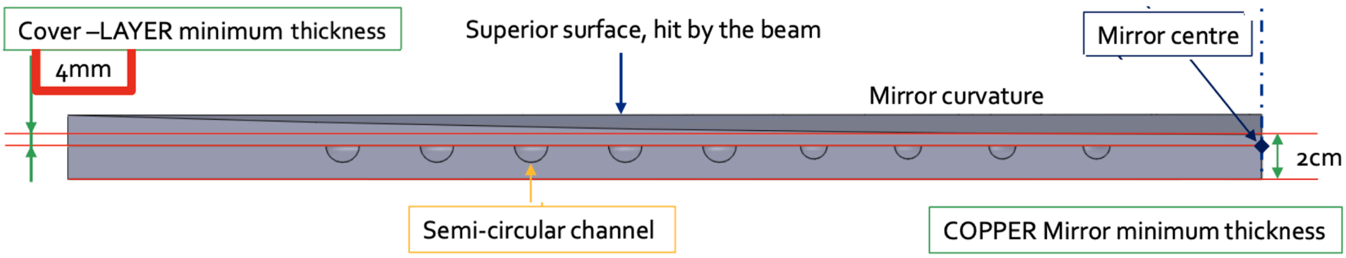

Fig. 10. Model of the mirror used in the calculations (only one half from edge to center is shown), with semicircular channels machined on a copper base and a copper layer realized on top.

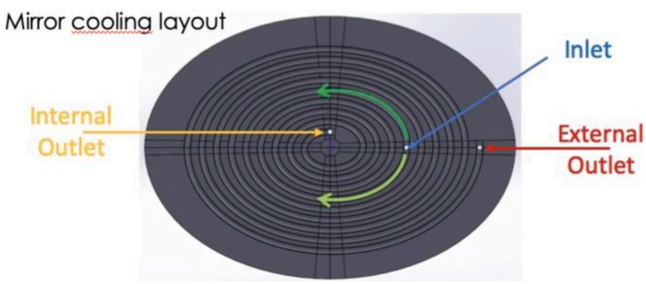

Fig. 11. Layout of the MB mirror cooling channels.

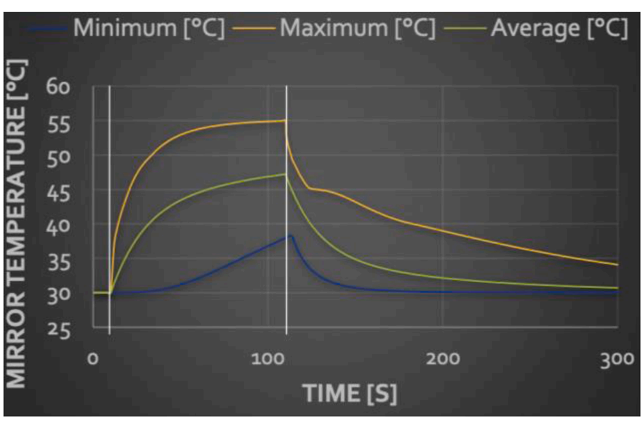

Fig. 12. Maximum, minimum and average mirror temperatures during a 100 s pulse at 1.5 MW per beam starting at 10 s.

replicated with the new deformations, a beneficial effect on the beam coupling.

In order to complete a consistent evaluation on the TL, three different models have been made for the mirrors in the main MBTL. They correspond to the parabolic one, the flat one with parallel beams in input (the one placed on a path where beams are parallel) and the flat with converging/diverging beams. The last one is on a path where the beams are crossing, and the beam spots are located on a different radial position. The losses are evaluated with GRASP at the time corresponding to the maximum deformation of the parabolic mirrors.

The coupling losses between input and output Gaussian beams are about 3.3% for all beams in the straight MBTL at 1.5 MW power level each, in the worst-case polarization. Losses at power scaled down at 1 MW and with a more favourable polarization (reflection close to H-Plane) are reduced by about a factor of two.

The analysis of the effect of deformations on the reduced model are progressing, considering the deformations on the other mirrors of the MBTL. Further reductions of mirror deformations with optimization of cooling layout and improvements of mirror stiffness are possible.

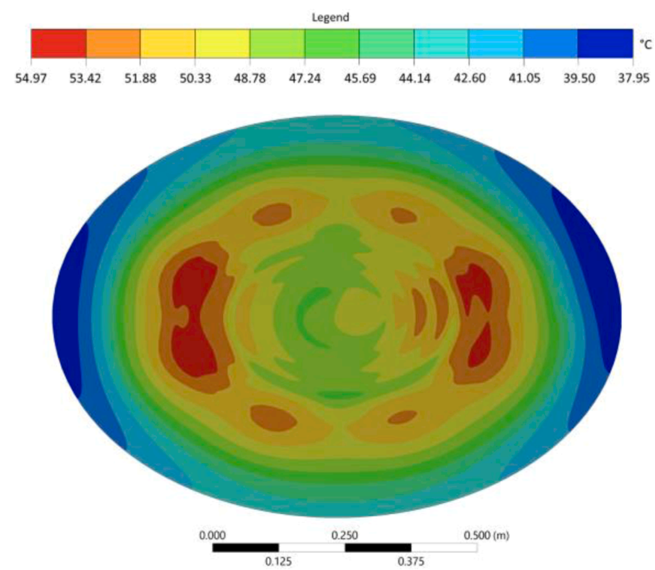

Fig. 13. Temperature on the mirror surface after a 100 s pulse at 1.5 MW per beam.

4. Single-Beam transmission to the launcher

In order to route the beams individually from the splitting mirror unit, located at the end of the MBTL in the THB up to the EC launchers (see [21]), a set of 3 mirrors for each beam line are necessary. The mirror ensemble represents the ex-vessel QO section of the TL. A picture representing the ex-vessel mirrors and the beam paths up to the upper and the equatorial antennas is shown in Fig. 14.

At the splitting mirror unit, placed where the parallel beams of the octagonal bundle have the minimum (waist) size and the maximum separation, eight plane splitter mirrors direct two of the beams toward the upper antenna and six to the equatorial antenna. A single focusing mirror is needed to match the beam from the splitter with the one entering into the antenna. Three different types of focusing mirrors are needed for the system.

A universal quasi-optical polarizing unit composed by two corrugated mirrors with $\lambda/8$ deep corrugations are foreseen for each line in a 45 deg. sharp dog-leg bend (22.5 deg. incidence angle). These units are placed between the focusing mirror and the antenna input. The polarizing mirrors rotation angles will be controlled in real time in order to launch the correct (ordinary or extraordinary) linear or elliptically polarized wave into the plasma when the launcher mirror [22] is steered. At the antenna input the Gaussian beams will be coupled into a waveguide or a tapering unit.

5. Ancillary systems

The ex-vessel mirror unit as well as the whole MBTL is enclosed in a

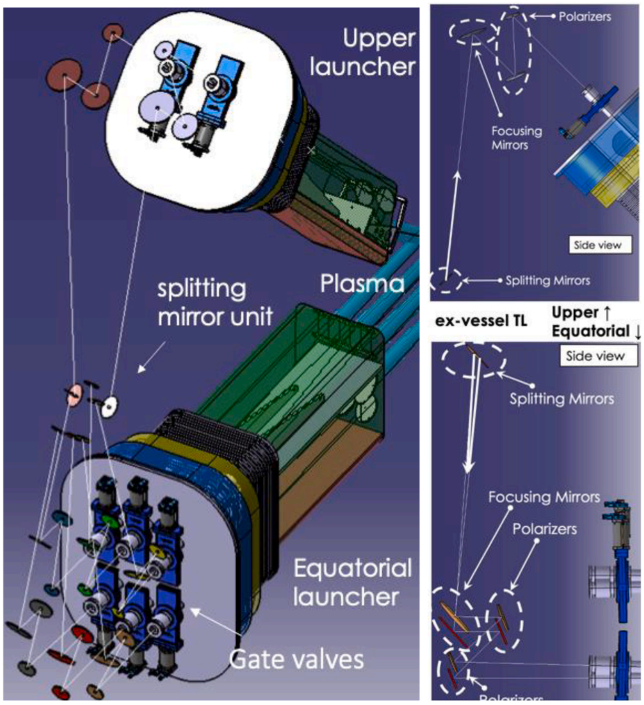

Fig. 14. Ex-vessel transmission lines in front of the upper and equatorial antennas.

large vacuum chamber extending from the gyrotron hall to the Torus Building. The choice has been taken in order to avoid power losses and possible arcing in air and to prevent microwave leaks to the environment. The vacuum enclosure of the whole line is in fact mainly realized with cylindrical tube sections with the use of metallic gaskets.

The need to keep the tightness in the MBTL suggests the use of elastic spring-loaded metallic gaskets as seals and bellows in specific points to cope with the envelope thermal expansion. The pumping system, suitable to maintain the desired pressure lower than 10^{-5} mbar in the very large volume, consists of two units placed at the beginning and the end of the MBTL. Each one consists of a dry fore-vacuum pump combined with a Roots pump for high gas loads, while a turbomolecular pump is used to reach the high-vacuum regime.

Gate valves mounted on the port flanges (shown in blue in Fig. 14) will separate the TL vacuum to the DTT vacuum when a specific ECRH line is not operating. In case of problems due to the interconnection of the two vacuum systems during the ECRH pulse into the plasma, diamond windows could be added in a later stage in front of the vacuum valves. The beam optics has been made compatible with a RF window unit insertion.

Misalignment tolerances were modeled with a Monte Carlo analysis of the geometric optics path of the central ray of each beam. Without a pre-alignment or an automatic alignment system they are very tight (of the order of 0.1 mrad for the tilt for the MBTL mirrors and 1 mrad for the SBTL mirrors) to have the beam position mismatch with a standard deviation of 5 mm. An automatic remote-controlled alignment system for the MBTL is being studied. This is based on a laser beam inserted at the beginning of the MBTL and reflected at the center of every mirror, optically polished. It will act on the orientation of at least 2 mirrors of the MBTL with the aim to recover small misalignment occurring after the pre-alignment, in order to check and keep the alignment through time even without opening the vacuum enclosure.

Microwave alignment of single beams is done with the line in air, after the MBTL has been pre-aligned with the laser, while alignment of single beams under vacuum would require beam alignment diagnostics that are presently being considered, but not assessed yet.

6. Next steps

Evaluations with the electromagnetic software GRASP of the complete line including deformations with an improved mirror cooling will be performed to qualify the impact of expected losses.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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