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Development of the electron cyclotron resonance heating system for Divertor Tokamak Test

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Saul Garavaglia ; Luca Balbinot ; Alessandro Bruschi ; Daniele Busi ; Andrea Bussolan; Francesco Fanale; Gustavo Granucci ; Alessandro Moro ; Paola Platania ; Natale Rispoli ; Afra Romano ; Emanuele Sartori ; Stefan Schmuck ; Alessandro Simonetto ; Espedito Vassallo 



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Saul Garavaglia,^{1,a)} Luca Balbinot,² Alessandro Bruschi,¹ Daniele Busi,³ Andrea Bussolan,¹ Francesco Fanale,^{4,5} Gustavo Granucci,¹ Alessandro Moro,¹ Paola Platania,¹ Natale Rispoli,¹ Afra Romano,^{4,5} Emanuele Sartori,² Stefan Schmuck,¹ Alessandro Simonetto,¹ and Espedito Vassallo¹

AFFILIATIONS

¹Institute for Plasma Science and Technology—CNR, via Cozzi 53, 20125 Milano, Italy

²Consorzio RFX, Corso Stati Uniti 4, 35127 Padova, Italy

³Department of Mechanical Engineering, Politecnico di Milano, via La Masa 1, 20156 Milan, Italy

⁴ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, via E. Fermi 45 00044, Frascati, Italy

⁵DTT S.c. a r. l., C. R. Frascati, via E. Fermi 45 00044, Frascati, Italy

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^{a)}Author to whom correspondence should be addressed: saul.garavaglia@istp.cnr.it

ABSTRACT

The Divertor Tokamak Test (DTT) facility, whose construction has started in Frascati (Italy), will be equipped with an ECRH (electron cyclotron resonance heating) system including 32 gyrotrons as microwave power sources. The procurement of the first batch of sources with 16 MW total power, based on 170 GHz/ ≥ 1 MW/100 s vacuum tubes, is in progress and will be available for the first DTT plasma. The system is organized into four clusters of 8 gyrotrons each. The power is transmitted from the Gyrotron Hall to the Torus Hall Building (THB) by a quasioptical transmission line (TL), mainly composed of large mirrors shared by eight beams coming from eight different gyrotrons and designed for up to 1.5 MW power per single beam, similar to the TL installed at the stellarator W7-X. One of novelties introduced in the DTT system is that the mirrors of the TLs are embodied in a vacuum enclosure, using large metal seals, mainly to avoid air absorption and risk of arcs. The main reason is to reduce the risk of air breakdown, maintaining a pressure of 10^{-5} mbar far away from the Paschen minimum. The TL estimated volume is between ~ 70 and ~ 85 m³. The direct connection of the TL to the tokamak vacuum vessel has been evaluated, and different solutions have been proposed in order to prevent a possible impact on DTT operations. The microwave power is injected into the tokamak using independent single-beam front-steering launchers, real-time controlled and located in the equatorial and upper ports of four DTT sectors. In-vessel piezoelectric walking drives are the most promising candidates for the launcher mirror movement considering their compactness and capability to operate in an environment with strong magnetic field under ultra-high vacuum. The DTT ECRH system design, presented here, is based mainly on existing and assessed solutions, although the challenging adaptations to the DTT case are considered.

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I. INTRODUCTION

The Divertor Tokamak Test (DTT) facility¹ is a medium-size research tokamak ($B_T = 6$ 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 Frascati (Rome). The European Fusion Roadmap² identified a list of eight challenges toward the electricity production from

thermonuclear fusion energy. The contribution of DTT is focused on the mission aimed to explore and test a reliable solution for the control of the power exhaust energy and particles issue from a fusion reactor.³ In future tokamak reactors, the plasma-facing components shall withstand the fluxes up to 10–20 MW/m². The heat load and exhaust impurity particles from the plasma are dealt with

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the use of a dedicated component, the divertor, located in the bottom of the machine chamber. DTT is designed with a high flexibility to test different divertor concepts and magnetic configurations in an integrated scenario compatible with plasma and technological constraints of the future demonstration reactor DEMO. For this purpose, a large amount of power shall be injected into the plasma in order to reach a similar value expected for DEMO of the power crossing the separatrix over the major radius of about 15 MW m^{-1} . In order to do so, 45 MW of additional heating power systems have been selected exploiting ion cyclotron resonance heating, neutral beam injection, and electron cyclotron resonance heating (ECRH). The latter that will provide up to 33.6 MW in its final configuration (Fig. 1).⁴

ECRH bases on the injection of microwave beams into the tokamak vessel at a frequency close to the gyration frequency of electrons located in the plasma center. These resonant microwaves are absorbed by the electrons, increasing the electron temperature and equilibrating with the ions by collisions and, therefore, increasing the overall plasma temperature.⁵ Many future fusion devices will rely heavily, if not solely, on ECRH heating systems for their flexible capability to accomplish different tasks: assisted breakdown to start the plasma discharge, assistance to ramp-up and ramp-down of the plasma current, bulk plasma heating, current drive and wall cleaning. In addition, ECRH is a prime tool for the plasma instability control and suppression for its surgical feature to deposit power in a very narrow and precise position. This paper describes

the status of the DTT ECRH system development, particularly focused on the study of the evacuated TL solutions.

II. SYSTEM DEVELOPMENT

The development strategy of the system is based on high reliability, high modularity, and reduced maintenance: existing and assessed technologies are favored to accomplish the ambitious schedule which calls for the first plasma in 2028. An ECRH system is mainly composed by microwave sources to generate radio frequency power, a transmission line (TL) to transmit the power toward the tokamak and antennas to inject the microwaves into the plasma. The plan of ECRH power installation foresees 8 gyrotrons available in 2028 for the first plasma operations, additional 8 in 2030 for first divertor test and further 16 gyrotrons in 2036 for the final operational stage. For this reason, the sources are organized into four clusters, each one composed of eight gyrotrons fed in pairs by four main high voltage power supplies (HVPS), one evacuated quasi-optical (QO) single-/multi-beam TL (SBTL/MBTL) and eight independent pairs of launching mirrors located in port 3 (equatorial antenna, 6 lines) and in port 2 (upper antenna, 2 lines). The general layout is shown in Fig. 2. The building dedicated to ECRH is organized on three levels: the basement with the cooling system and the electrical substation, the ground level with the 16 HVPS modules and the first level with 32 gyrotrons. The four TLs pass from this building to the THB along the bridge, cross the bioshield of the THB just above the equatorial plane of the machine and reach the upper and the equatorial ports of the four DTT sectors (12, 14, 16, and 18).⁶

The unit power source is a gyrotron, a high-power electronic vacuum tube, able to generate electromagnetic waves at mm-wave frequency by the cyclotron resonance of electrons in a strong magnetic field. The reference gyrotron is a diode-type, with collector voltage depression and a cryo-magnet, operating at $170 \text{ GHz} \pm 0.3 \text{ GHz}$ (as for ITER), to resonate at DTT's toroidal magnet field of $B_T \sim 6 \text{ T}$ at the vessel center), with an efficiency of $\sim 40\%$ to yield 1–1.2 MW for 100 s. A joint procurement with fusion for energy is started for the provision of the first 16 gyrotrons for DTT and 6 for ITER. The acceptance of the first preseries gyrotron is foreseen in the second part of 2023 and the completion of the first cluster within 2027.⁷

A. Transmission line

The main requirements for the TL are a target transmission efficiency of 90% and a power handling capability of up to 1.5 MW per single beam, which enables an upgrade for the gyrotron output power. The transmission of the microwave power generated by the gyrotrons is realized by reflections at focusing and planar mirrors (metallic reflecting surfaces) in a confocal arrangement. The TL concept is based on the QO propagation of Gaussian beams at 170 GHz and it is modeled with standard QO theory. For the most part, the TL exploits the multiple beam option with eight beams sharing oversized parabolic and plane mirrors, similar to the concept of the W7-X TL.⁸ The beams propagate alternately crossing or parallel to each other between two following focusing mirrors (Fig. 3). The TL design strategy is a trade-off between the mirror dimension (related directly to the beam radius on the mirror surface) and the distance between two following focusing

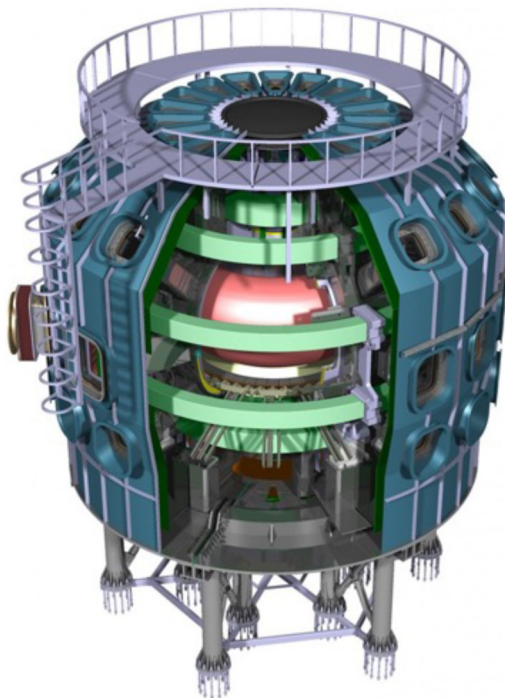


FIG. 1. Image of DTT showing internal components.

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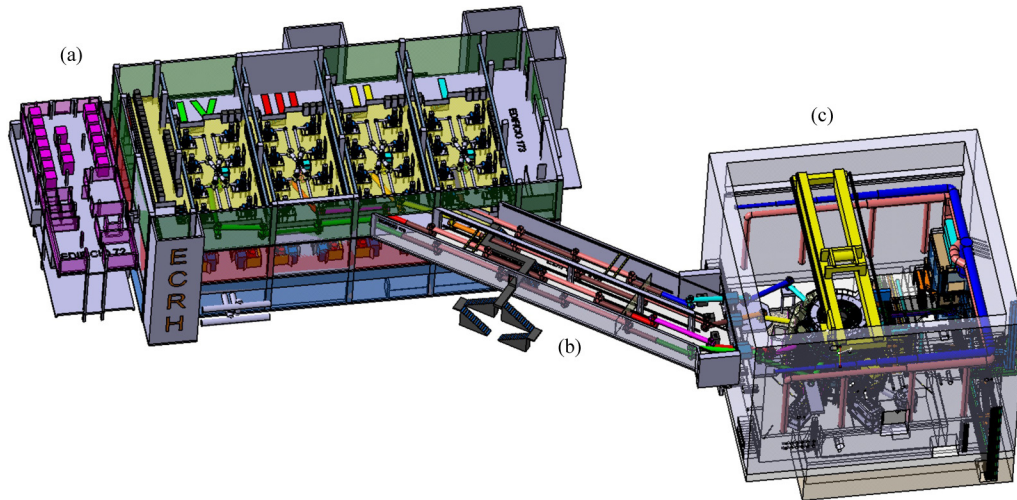


FIG. 2. ECRH building (a), the Torus Hall Building, (c) and the joining bridge (b).

mirrors. One of the novelties incorporated for the first time is the enclosure of the TL under vacuum using large metal seals in order to minimize the transmission losses and the arc risk in air.

The TL is divided into three parts (Fig. 4): the first part, i.e., the SBTL connects each source of one cluster to the so-called combining at the geometrical center of the cluster, where eight beams are combined to a single bundle [Fig. 5(a)]. From this point, a MBTL delivers the beams up to the THB. The main MBTL consists of a straight section running along the corridor. At both of its ends, the connections have been realized by a telescopic mirror arrangement to reach on one side the combining mirror at the center of the gyrotrons cluster and on the other side the splitting mirror in front of each of the dedicated ECRH tokamak sectors. The eight beams are arranged on the vertices of an ideal octagon at the start and end of the MBTL. At these interfaces, the beams travel in parallel. In the last part of the TL, the eight beams are divided: six are directed toward port 3 and two toward port 2 where the equatorial and upper antennas are, respectively, located [Fig. 5(b)].

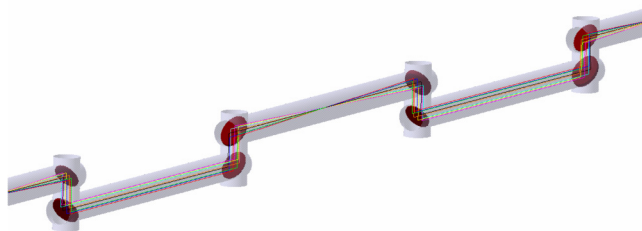


FIG. 3. Model of the MBTL unit which is composed of four focusing mirrors alternated with four flat mirrors in alternating order.

The number of mirrors for one representative beam of each of the 4 TLs is reported in Table I. The mirrors have an elliptical shape with dimensions of $\sim 1.1 \times \sim 0.8$ m for MBTL and $\sim 0.35 \times \sim 0.25$ m for SBTL to reflect about 99.97% of the incident power. Each mirror consists of a copper alloy body with ~ 20 mm thickness and a few mm of a pure copper coating. The mirrors are water cooled via a double spiral circuit to maintain the lowest temperature increase of the reflectors and the minimum surface deformation induced by temperature inhomogeneity.¹⁰

The TL models have been verified with the use of GRASP¹¹ evaluating the propagating power density and the losses. The following results refer to the ideal case, for which it is assumed that the TL is optically aligned and mirror surfaces remain undeformed.

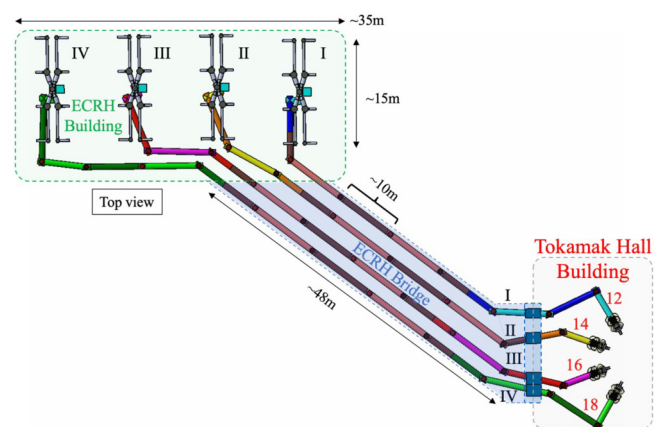


FIG. 4. Top view of TLs: the SBTL into the ECRH building (small gray tubes), the MBTL (large colored tubes) along the bridge and on the penetration in the Tokamak Hall Building with the connections into the DTT dedicated sectors.

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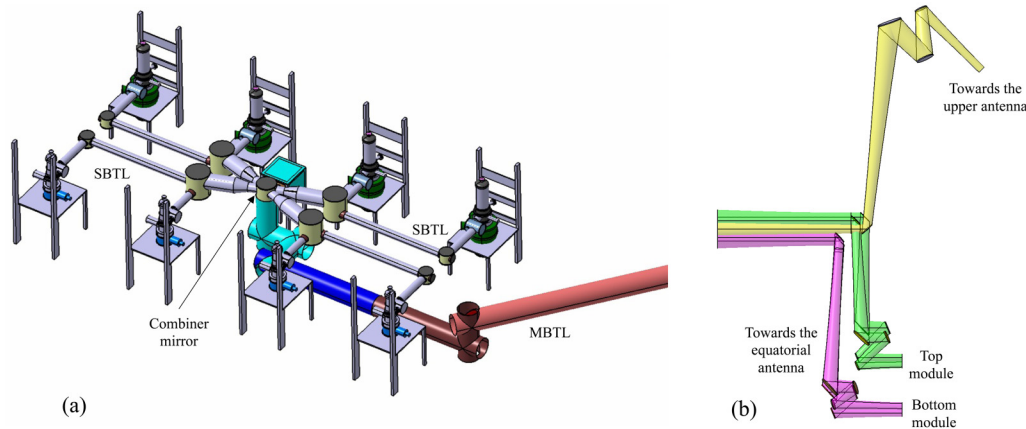


FIG. 5. (a) ECRH cluster with eight gyrotrons, the SBT that connect each gyrotron to the combiner mirror at the center where the MBTL starts below indicated by the blue and red tubes. The cyan cube is the RF load. (b) SBT path in tokamak hall. Two beams (yellow) are directed towards the upper antenna. Three beams are directed each toward the bottom (magenta) and the top (green) modules of the equatorial antenna.

In the modular straight part of the MBTL (ECRH bridge) the losses due to high order modes content and spillover (i.e., power radiated outside the mirrors) are low as expected (0.16%), while the losses are higher in the others sections of the MBTL (between 2% and 2.35% depending on the TL). The role of spillover losses only, considering the finite dimensions of all the mirrors is of the order of 1% for the four TLs and the chosen mirrors size, which means that the radiated power not intercepted by the mirrors and enclosed in the vacuum chamber is of the order of 80 kW per line. According to the final decision on the vacuum enclosure material, specific parts of the vacuum envelope could be internally coated with microwave-absorbing material or water cooled to dissipate the power scattered. The ohmic losses, depending on the polarization selected at the input, range between 2.2% and 4.0% including a factor of 1.3 for the mirror roughness.¹² 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. A more realistic and all-inclusive estimate of losses is ongoing with 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) and the calculation of the required tolerances in the alignment of the mirrors with an approach based on Monte Carlo analysis and geometric optics.¹³

TABLE I. Number of mirrors for the MBTL, for the TL (SBTL + MBTL), the path length, the internal surface and the volume of TLs.

TL	MBTL mirrors	Total mirrors	Length (m)	Surface (m ²)	Volume (m ³)
I	17	77	84–90	360	68
II	17	71	89–95	373	71
II	21	81	104–110	416	78
IV	25	85	130–137.5	470	87

B. Launcher

In four DTT sectors, two different antennas are hosted in the equatorial and in the upper ports, equipped with 6 and 2 launchers, respectively [Fig. 6(a)]. The eight launchers per cluster are almost identical and independently steerable to increase the modularity and the flexibility. They are based on the front steering concept and consist of two mirrors in a dogleg arrangement, made in CuCrZr alloy. The first mirror (M1) is fixed and re-focuses the beam arriving from the TL. The second mirror (M2), facing to the plasma, is flat and steerable in both poloidal and toroidal directions to direct the beam in a precise location into the vessel [Fig. 6(b)].

The poloidal steering angular range is from 20° to 50° for upper launchers and from −25° to 10° (top module) or from −10° to 25° (bottom module) for the equatorial launchers; ±25° is the toroidal steering angular range for all launchers. The launcher mirror dimensions are, respectively, 138 × 196 mm for M1 and ~138 × 264 mm for M2. Both mirrors are water cooled through an elliptical spiral channel. Computational fluid dynamics simulations followed by thermo-mechanical and thermo-dynamical analyses are in progress to optimize the cooling.¹⁴

An extensive R&D activity is ongoing to deliver an innovative M2 mirror actuator and driving mechanism, with flexible cooling tubes and position sensors. The steering mechanism shall be very compact to fit the reduced space available outside the port flange or inside the port. This requirement suggests to avoid mechanical vacuum feedthroughs and to prefer a fully in-vessel actuator. This kind of solution implies the choice of an actuator ultra-high vacuum compatible, subject to nuclear (neutron and gamma) irradiation, microwave stray radiation and strong variable magnetic fields. The proposed candidate is a piezoelectric walking drive, compliant with most of these conditions.¹⁵ The main drawback is the limited driving force (the maximum allowable torque in the poloidal direction is 2 N m) with respect to the external torques

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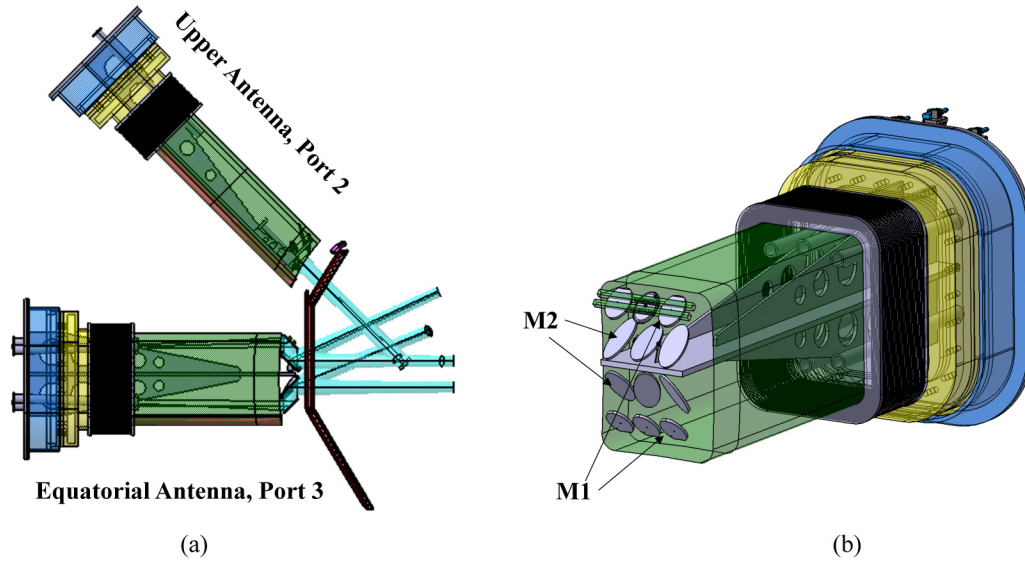


FIG. 6. (a) Upper and equatorial antennas of one DTT sector. (b) Front of the equatorial antenna with mirrors M1 and M2.

expected on the CuCrZr mirror because of variable magnetic fields, as those induced by the nonaxisymmetric in-vessel coils for plasma control, especially during disruption events of the tokamak. Alternative options under examination are the realization of the mirror in AISI 316LN or dielectric with coating of few microns of Cu or W.

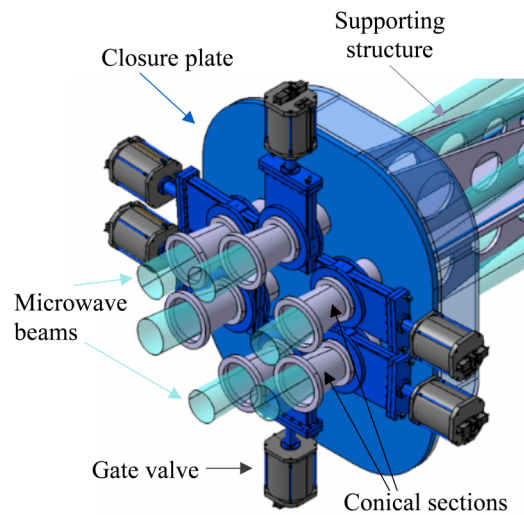


FIG. 7. General back view of the equatorial antenna with the conical sections to connect the TL with the DTT vessel and the gate valves. In gray, the supporting structure, in blue the closure plate and in light cyan the microwave beams propagation.

C. Vacuum system

In the ECRH systems based on QO TL for the stellarator W7-X,⁸ the beams propagate in a controlled dry air environment to significantly decrease the losses (estimated from 7% to 11% with 50% humidity depending on the TL length) and the risk of arcing. This solution requires that the duct of the TL is equipped with a powerful air-drying system which brings down the relative humidity. Such a system is not accessible during the ECRH discharge for safety reasons. To reduce the nonaccessible space, the mirrors could be enclosed in an air-conditioned pipe, which would require an additional mm-wave leak control at each junction for safety reasons. The novelty of the TL propagation under vacuum drastically reduces the losses, the arcing risk and prevents the mm-waves stray leakage. The enclosure is a cylindrical chamber containing the beam paths and the mirrors with related structures, realized in stainless steel (a lighter option in aluminum is under evaluation) with a diameter of 800 mm (300 mm) and thickness of 6 mm (3 mm) for the MBTL (SBTL). The main components are boxes and towers, containing one or two mirrors, and are connected to each other by pipes with maximum length of 10 m, with some bellows to accommodate thermal expansion. The Ex-Vessel Optics Unit, the last section of the TL, is located in the tokamak hall with a height of 5.5 m. The target pressure in the enclosure is ~ 1 mPa.

A preliminary design of the pumping for the DTT ECRH TL system was carried out as a function of volume to be pumped out and surface of the vacuum chamber. For each TL, two pumping systems are planned, one near the gyrotron clusters and the other close to the THB in the corridor. Each set consists of a dry fore-vacuum pump combined with a Roots pump for high gas loads, while a turbomolecular pump is used to get to the high vacuum regime (effective pumping speed in the range of 1300–1700 l/s as a

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function of volume and surface of each TL involved) in ~ 15 min. These pumps are able to absorb the hydrogen possibly flowed in the TL duct from the tokamak. The removal of the absorbed gas of the pumps is accomplished in air atmosphere allowing the human access in the ECRH buildings during operation.

In a first preliminary design, each TL volume (see Table I) was connected to the DTT vessel volume ($\sim 100 \text{ m}^3$ at a pressure of $\sim 10^{-2}$ – 10^{-3} mPa, ~ 10 mPa during the discharge) via 8 conical openings with a diameter of 150 and 450 mm long [Fig. 7]. The connection between the vacuum vessel and TL will be regulated only by all-metal gate valves without a separating torus window used in other tokamaks. These valves are normally closed and are opened a few seconds before the start of the plasma discharge and closed after the ECRH emission. When the TL and tokamak volumes are connected, during the DTT pulse, the gas introduced into the tokamak can flow to the TLs, where a higher vacuum condition is required.

In this condition, the gas flow regime transits between the viscous and molecular regimes. The vacuum system dynamics between the tokamak and TL has been studied by a lumped model. A three-dimensional model of the gas flow in the molecular regime was simulated with AVOCADO,¹⁶ including the actual geometry to a certain degree. During a plasma discharge, neutrals are present in the plasma edge and scrape-off layer. Plasma particles are recycled as neutrals at the walls and desorb adsorbed molecules; charge-exchange events let fast neutrals reach the wall; gas is injected at the plasma edge and is scattered and can move in the SOL until it is ionized. Dedicated models like SOLEDGE2D-EIRENE¹⁷ and SOLPS-ITER¹⁸ are used to simulate the edge plasma conditions during plasma discharges for various scenarios. SOLEDGE2D-EIRENE mesh can be extended to the first wall with a penalization technique; thus, the code was used in this study to estimate the neutral pressure in the main chamber in front of ECRH ducts during flat top operations. Simulations performed are described in Ref. 19, while Fig. 8 shows the simulation output in terms of atomic and molecular densities and temperatures, which are used to evaluate the particle distribution along the ducts with AVOCADO.

Figure 9(a) shows the transient calculation of hydrogen pressure in the torus ($p_{\text{VACUUM VESSEL}}$, corresponding to an equilibrium between injected gas throughput and effective pumping speed) and at two ends of the TL (gyrotron and launcher sides). According to the simulation, when the gate valves open ($t = 0$ s) the TL pressure increases rapidly, due to the very large volume of the MBTL enclosure, reaching almost the equilibrium with the torus pressure despite the presence of turbomolecular pumps with the pumping speed of 1400 l/s. The solid line indicates a fixed gas puffing in the torus with response of neutral dynamics at the plasma edge being faster than response of the gas flow in the TL. The dashed line considers a feedback control of the gas puffing in the torus. Figure 9(b) reports the evolution of the gas throughput for the same case. During the plasma discharge, a similar effect is expected with a gas flow from the tokamak toward TL one order of magnitude lower than the gas flow injected in the DTT vacuum vessel to sustain the plasma density.

A drastic reduction of conductance between the TL and vacuum vessel is necessary to avoid compromised plasma operation. For this

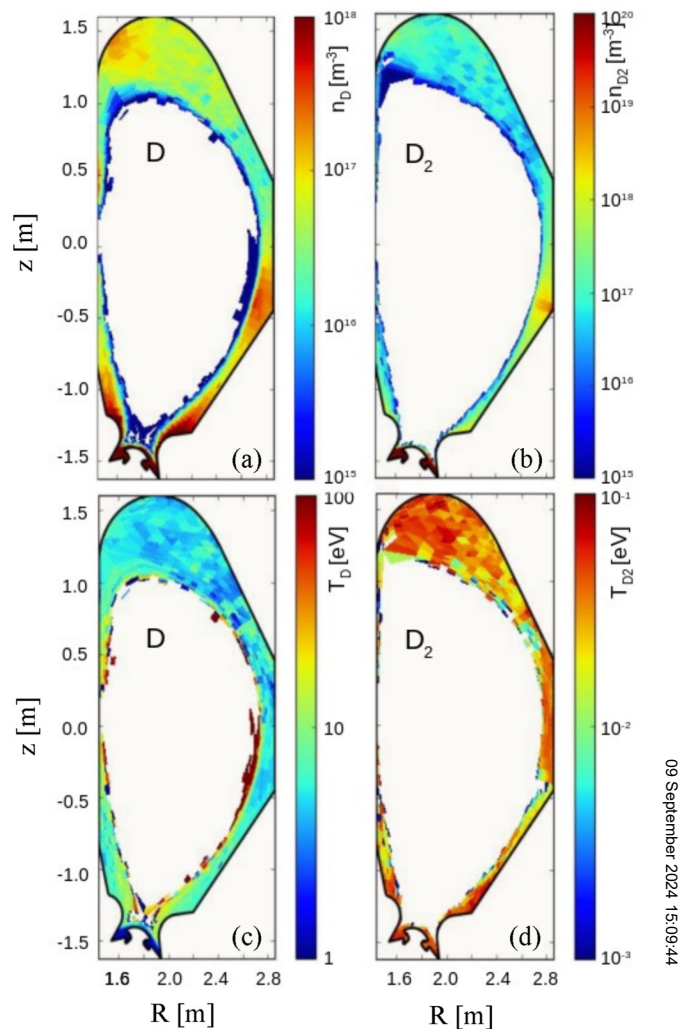


FIG. 8. Edge simulations: density (at the top) and temperature (at the bottom) of atoms (on the left) and molecules (on the right) in one plasma scenario for deuterium discharge density of atoms (a) molecules, (b) and temperature of atoms (c) molecules (d) in one plasma scenario for deuterium discharge.

reason, a section of cooled corrugated waveguide (WG) ~ 1.5 m long with internal diameter of 63.5 mm in copper or copper-/nickel-coated steel (Fig. 10) has been inserted between the SBTL enclosure and the plug-in launcher [Fig. 6(b)], reducing the conductance of those elements down to 2.3%. From preliminary analysis, the possibility of plasma breakdown in the port does not seem to be a serious concern, because the second harmonic layer is located between the end of the WG and the M1 mirror, where the beam travels in free space and its path is sufficiently far from any conducting sharp edge. A more detailed assessment of the magnetic field map inside the port is foreseen to identify potential critical points.

The corrugation of 0.4 mm in depth of the inner surfaces of the WG would contribute in reducing the gas conductance of the

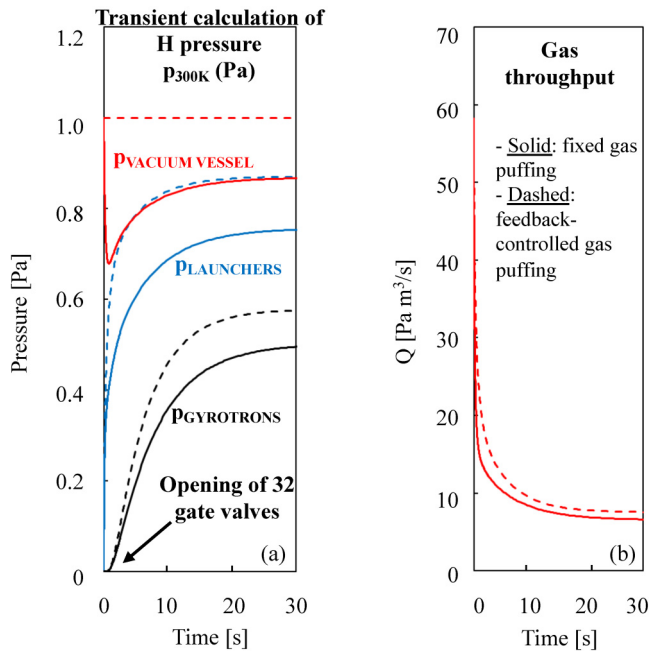


FIG. 9. (a) Transient calculation of hydrogen pressure of the torus ($P_{\text{VACUUM VESSEL}}$) and at both ends of TL. (b) Evolution of the gas throughput. The solid lines indicate a fixed gas puffing and the dashed lines consider a feedback control in the torus.

WG with respect of a smooth tube (see, for instance, the effect of a finned geometry of the tube walls²⁰). On the other hand, approximating the gas regime to the free molecular regime provides an underestimation of the conductance.²¹ For the purpose of this analysis, we will consider the free molecular limit, neglecting both the reduction of gas conductance due to corrugated waveguide (which would reduce the conductance by about 20%) and the possible

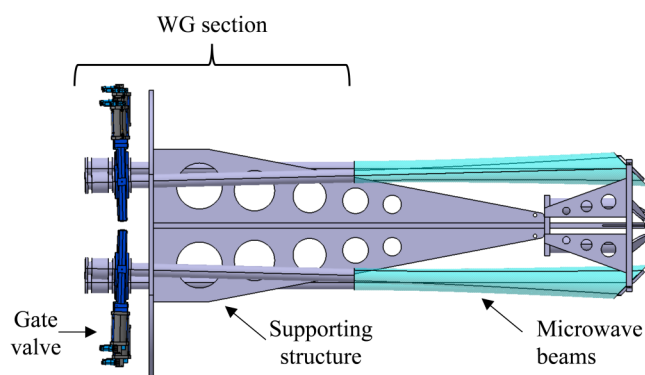


FIG. 10. Side view of the equatorial antenna with its supporting structure. In blue the safety gate valve and in gray the WG sections. Cyan surfaces represent the microwave beams propagation inside the antenna.

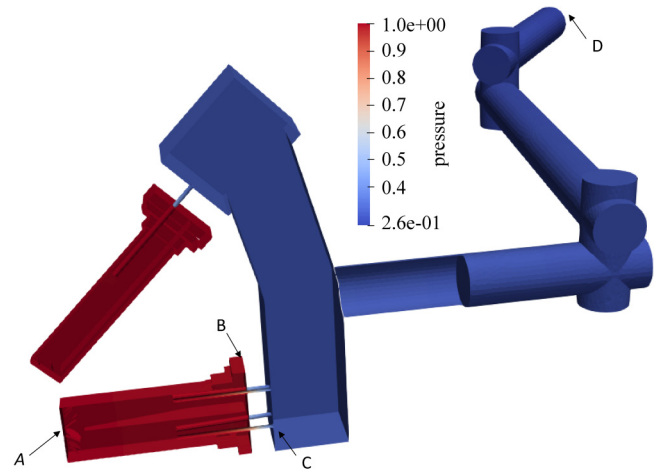


FIG. 11. Domain of the numerical simulation of the gas conductance in the molecular regime. A normalized pressure has been used to calculate the conductances; the pressure gradient is localized at along the eight WG. The letters A, B, C, and D indicate the positions between conductance and are calculated in Table II.

increase of conductance due to gas viscosity (which is lower than 8% taking an effective hydrogen pressure of 0.5 Pa), thus yielding an upper limit to the conductance (i.e., conservative approach). The new geometry was evaluated both analytically and with the support of three-dimensional numerical simulations, as shown in Fig. 11, from the plasma edge up to the first pumping section of the TL.

Table II reports the analytical gas conductance in the molecular regime between the launcher region and the transmission line, calculated considering only the six 1.45 m long waveguides for the equatorial antenna; the numerical result includes also the conductances of the other segments, from the tokamak port to the first pumping section of the transmission line. A detailed view of the launcher section is shown in Fig. 12(a).

The conductance for hydrogen of the transmission lines was calculated including the first TL dogleg and the presence of mirrors, considering the submodel of Fig. 12(b). In particular, the calculated conductance including the TL dogleg, and two segments of transmission line tubes (each 4.0 m long, about half the distance

TABLE II. Conductances in the molecular regime from the plasma edge to the first pumping section of the TL; the positions indicated by letters A, B, C, and D are shown in Fig. 11.

	Analytical conductance	Numerical conductance
Equatorial port (A-B)	—	120 m ³ /s
Equatorial WG (B-C)	0.55 m ³ /s (six WGs)	0.544 m ³ /s (six WGs)
From WG to turbopumps (C-D)	12.3 m ³ /s (18.3 m straight tube)	11.14 m ³ /s

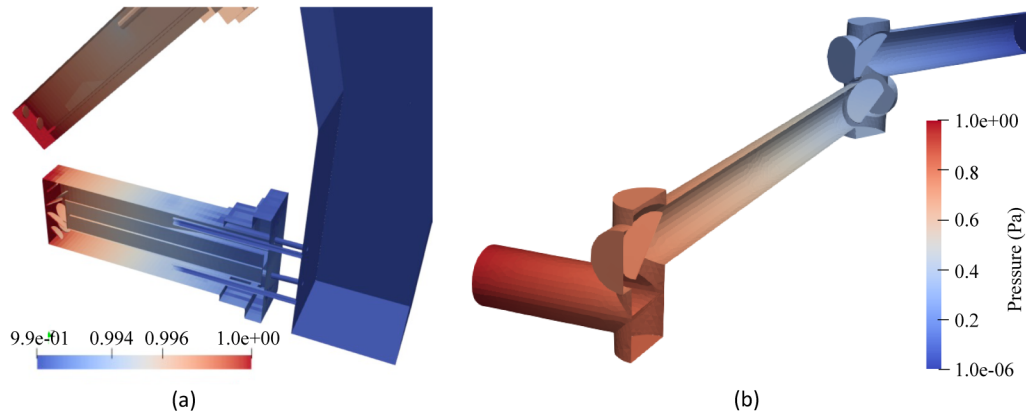


FIG. 12. (a) Detailed view of normalized pressure distribution inside launchers; (b) submodel of a TL segment composed by two doglegs with mirrors.

between two mirrors) with mirrors, is $12.3 \text{ m}^3/\text{s}$. This value can be compared to the analytical conductance of a straight segment of a cylindrical tube, having the same linear length of the three-dimensional geometry of 16.3 m long, which is $13.7 \text{ m}^3/\text{s}$, to obtain the localized conductance of each dogleg, of the order of $240 \text{ m}^3/\text{s}$.

The transient calculation of hydrogen pressure has been repeated with the updated geometry and, during the transient, the flow from the tokamak results to be below $4 \times 10^{20} \text{ mol/s}$ ($1.5 \text{ Pa m}^3/\text{s}$) with a marginal impact on the tokamak gas puffing (expected puffing $\sim 4\text{--}6 \times 10^{22} \text{ atoms/s}$ with deuterium). Figure 13(a) shows the updated hydrogen pressure, to be compared to the one in Fig. 9.

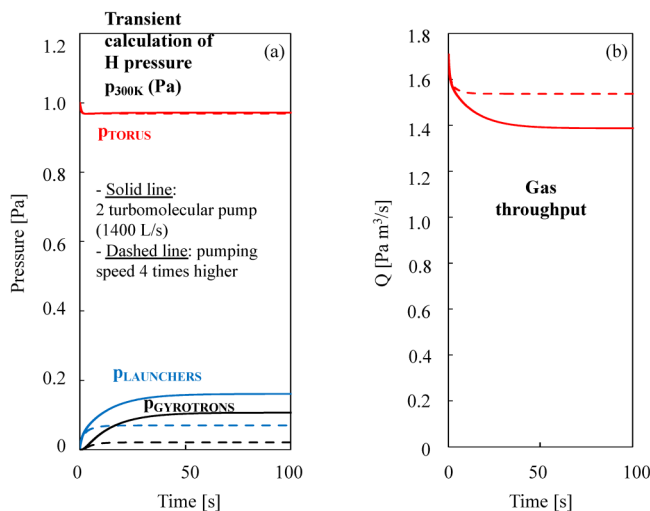


FIG. 13. (a) Transient calculation of hydrogen pressure of the torus (P_{TORUS}) and at two ends of TL. (b) The evolution of the gas throughput. The solid lines indicate one turbomolecular pump installed at each edge of the four MBTL, while the dashed lines show the case of a pumping speed four times higher.

Solid lines indicate the ones obtained with turbomolecular pumps installed at both ends of the MTBL (with pumping speed of 1400 l/s), while the dashed lines show the same case evaluated with a pumping speed four times higher in case the highest pressure will be verified not to be acceptable for the TL use.

In conclusion, this optimized configuration could allow the use of vacuum valves without a permanent Radio Frequency (RF) window. On the other hand, this solution requires the realization of a cooled WG section reducing the flexibility of the QO-setup. Moreover, the TL transition from free space to corrugated WG introduces an extra maximum loss contribution of 4% losses in TL amount, which can be reduced either by tuning the waveguide length and beam waist or by installing an optimized HE_{11} - TEM_{00} taper at least on one end. 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 diamond RF windows will remain possible. The optical design has consequently been made compatible with the insertion of a matching WG.

III. CONCLUSION

Progress in the development of the DTT's ECRH system is presented. The gyrotron procurement contract has been signed and the first gyrotron acceptance is foreseen in late 2023. The layout of the system has been consolidated with a modular architecture based on clusters. The design of the single/multibeam QO TL including the novel approach to evacuate the TL is extensively studied and different solutions to connect the TL and the tokamak volumes proposed. An innovative solution for the steering mirrors actuators is under development together with extended qualification test activities (actuator, cart-wheel, cooling tubes). The next efforts will be dedicated to complete and validate the TL conceptual design and the antenna.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Saul Garavaglia: Conceptualization (equal); Project administration (equal); Supervision (equal); Writing – original draft (equal). **Luca Balbinot:** Data curation (equal); Formal analysis (equal); Investigation (equal); Validation (equal); Writing – original draft (equal). **Alessandro Bruschi:** Conceptualization (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal). **Daniele Busi:** Conceptualization (equal); Investigation (equal); Software (equal); Validation (equal). **Andrea Bussolan:** Writing – original draft (equal). **Francesco Fanale:** Writing – original draft (equal). **Gustavo Granucci:** Conceptualization (equal); Supervision (equal). **Alessandro Moro:** Writing – original draft (equal). **Paola Platania:** Data curation (equal); Formal analysis (equal); Investigation (equal). **Natale Rispoli:** Writing – original draft (equal). **Afra Romano:** Writing – original draft (equal). **Emanuele Sartori:** Conceptualization (equal); Data curation (equal); Investigation (equal); Software (equal); Writing – original draft (equal). **Stefan Schmuck:** Writing – original draft (equal). **Alessandro Simonetto:** Writing – original draft (equal). **Espedito Vassallo:** Formal analysis (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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