

CONFERENCE PRE-PRINT**THE DIVERTOR TOKAMAK TEST PROJECT: PROGRESS TOWARDS THE INITIAL OPERATION**

F. ROMANELLI

DTT s.c.ar.l.

Frascati, Italy

Email: Francesco.romanelli@dt-project.it

DTT contributors

DTT s.c.ar.l.

Frascati, Italy

Abstract

The Divertor Tokamak Test (DTT) facility is a research infrastructure to investigate advanced solutions for the heat exhaust in tokamaks. The status of the construction and the elaboration of the research plan are presented.

1. INTRODUCTION

The Divertor Tokamak Test (DTT) facility [1] is an experiment specifically designed to address the challenge of the heat exhaust in fusion experiments. DTT will achieve ITER and DEMO relevant heat loads, through a combination of substantial amount of additional heating (up to 45MW at the plasma) and compact dimensions ($R=2.19\text{m}$, $a=0.70\text{m}$, $B=5.85\text{T}$, $I_p=5.5\text{MA}$). DTT is a breakeven-class, long-pulse (100s) superconducting tokamak, equipped with full-tungsten, actively cooled plasma-facing components. The start of operation is foreseen at the beginning of the next decade, a few years in advance of the ITER achievement of full magnetic performance, making DTT an ideal test bed for the preparation of ITER exploitation. DTT has been designed with sufficient flexibility to investigate advanced magnetic configurations that allow large divertor wetted areas and advanced plasma facing components technology. The core-edge integration will be a crucial part of the research program with the investigation of high-confinement, high radiation regimes via impurity seeding. Finally, the potential of liquid metals for plasma facing components is foreseen to be an important part of the DTT program. At the start of operation, the machine will have 16MW of installed Electron Cyclotron Heating (ECH) power, 4MW of Ion cyclotron Heating (ICH) power and a set of basic diagnostics. The heating capability will be upgraded during the first decade of operation by a 10MW negative beam system (510keV) and additional diagnostics. At the end of the first decade of operation the machine will be further upgraded with 16MW of ECH power, 4MW of ICH power and a new divertor designed on the basis of the DEMO needs.

The first version of the DTT Research Plan has been released in 2024 and has been elaborated with the active involvement of several scientists from the Eurofusion laboratories. The main outcomes of this elaboration are discussed in Sec. 2.

Since the last IAEA meeting, the design of almost all the more complex parts of the project has been completed. To date, about 38% of the allocated budget is committed in completed or ongoing industrial contracts, tenders for about 18% of the allocated budget are either adjudicated or ongoing. Other large tenders (electrical distribution system, cryoplant, assembly, high voltage gyrotron power supply for about 23% of the allocated budget) are in the completion of documentation phase and will be launched before the end of the 2025.

The magnetic system is under construction. The production of the 18 winding packs of the Toroidal Field (TF) coils is in full swing with three already completed and tested. All the Nb_3Sn conductor for the TF magnet will be completed by the end of 2025. The new contract for the TF casing has been signed at the beginning of 2025 and the first casing is expected at the end of 2026. The TF power supply has been delivered to the Frascati site in 2024 and has been installed in the Frascati Cold Coil Test Facility (FCCCTF) where all the Nb_3Sn coils will be tested. Also, the first Fast Discharge Unit has been delivered to the Frascati site. The new call for tender for the poloidal system, consisting of 6 coils (PF1-6), 2 of which (PF1 and PF6) in Nb_3Sn and the others in NbTi , has been launched. The NbTi and the Nb_3Sn for the PF6 strand is already available while the rest of the Nb_3Sn (PF1 and central solenoid) is under procurement. The design choice for the central solenoid has been frozen around a conventional double pancake solution with a High Temperature Superconducting insert to ensure 33Vs of available flux. The delivery of the in-vessel coil systems power supply (for control of the strike point position and of the field in the divertor region, the plasma position control and the ELM control and error fields suppression) is expected in the first half of 2026.

The operating tools for the DTT Remote Handling (RH) system (a pair of HYper Redundant Manipulators – HyRMan - designed to operate, with a 300 kg payload, through dedicated access port and three cassette movers for divertor maintenance) are also under fabrication and will be delivered during 2026 to the RH facility near Naples where all the RH operation will be tested in advance.

The pre-series ECH gyrotron (1MW/170GHz/100s) has been successfully tested in 2023. The transmitters for the first 2MW ICH (60-90MHz using solid state technology) are under fabrication and their delivery is expected in the first half of 2026. The R&D for the 10 MW/510keV NBI system, planned to run in the second phase of machine operations, is progressing.

The critical path of the project is represented by the civil infrastructures and the assembly of the machine. The tender for the new buildings is under examination and the contract is expected to be signed at the beginning of 2026. Several preparatory activities (access opening, demolitions, medium voltage connection to the grid) are under execution to recover part of the delay. The call for tender for the new 150kV/20kV electric substation is expected to be launched before the end of 2025. In parallel, TERNA, the Italian grid transmission operator, is progressing with the construction of the 150kV line between the node of Rome east and ENEA.

2. THE DTT RESEARCH PLAN

The DTT Research Plan (DTT-RP) [2] describes the objectives and research strategy of the DTT experiment [1] and proposes a set of programmatic headlines of its scientific programme. The DTT-RP has been prepared starting in 2022 by an international team comprising approximately 100 European fusion scientists belonging to 20 research institutes from 10 different countries. The Research Plan will be regularly updated and will catalyse and guide the research activities in preparation of the experimental phase.

The Research Plan is based on the expected performance of DTT, which aims at establishing the device as one of the world's most advanced tokamaks in the next decade. DTT main mission is that of exploring solutions for managing plasma exhaust

in future fusion devices. To this purpose, DTT is equipped with full W actively cooled plasma facing components and has the capability of investigating various divertor configurations.

The Wide Flat Divertor has been presently

selected for DTT. Figure 1 shows magnetic geometries of divertor configurations accessible in DTT. Its compact size and large auxiliary heating power allow to achieve DEMO divertor heat loads and to produce ITER/DEMO relevant plasmas.

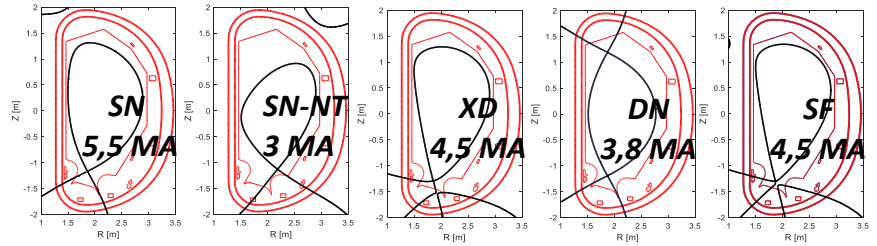


FIG. 1. Divertor configurations achievable on DTT.

Figure 2 compares a number of dimensionless parameters of DTT with those of ITER (2019) and DEMO (2018) baseline scenarios. For DTT, both the reference baseline scenario at 0.5 of the Greenwald density and one at 0.32 Greenwald density are shown. DTT has relevant dimensionless parameters close to those typical of ITER and DEMO-class reactors. Specifically: the wall load parameter $P_{\text{SOL}}/R \sim 15 \text{ MW/m}$, where P_{SOL}/R is the ratio of power flowing out the Scrape-Off-Layer (SOL) to major radius; simultaneous high edge density and low collisionality; scrape-off layer width similar to ITER and DEMO; ITER/DEMO relevant core confinement properties. The unique capabilities of DTT have been acknowledged by the international community. Notably, the 2024 EUROfusion Facilities Review report highlighted the potential of DTT "for major impact on the design of DEMO", as a device "ideal for testing ITER and DEMO scenarios in relevant conditions". Based on these considerations, DTT was classified by the Facilities Review international panel as one of the few "indispensable" tokamak facilities of the future European fusion programme, without which "the programme goals cannot be realized on the required timescale".

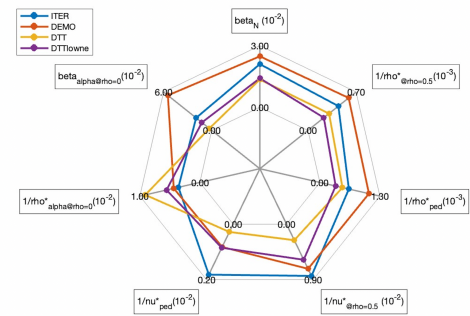


FIG. 2. DTT parameters compared with those of ITER and DEMO.

The DTT Research Program is organized in nine chapters and nine technical appendices, which provide a synthetic description of the device main characteristics; it follows the expected evolution of the machine along three distinct phases of machine upgrades, as described in the introduction. The main top-level headlines of the DTT scientific contribution to the European fusion programme, in support to ITER and in preparation of DEMO, are the following.

Development and assessment of baseline and advanced scenarios for the various divertor configurations shown in Figure 1, at nominal field and current, for performance comparison (note that change of divertor configuration may happen within the same discharge). Figure 3 from Ref.[3] shows the 1-d full power baseline scenarios profiles simulated with TGLF and QLK [3]. Experiments in AUG and TCV, as well as gyrokinetic simulations and transport predictions, are ongoing to investigate whether a Negative Triangularity L-mode for DTT full-power scenario would perform similarly to the positive triangularity H-mode reference scenario avoiding ELMs [4].

Development of scenarios at half field and current, with 2nd harmonic ECRH heating, to study high β_N regimes. These studies, carried out in a full tungsten device, will benefit also from the system for MHD feedback control, based on 27 active coils (3 toroidal rows with 9 coils each, with a geometry similar to that of ITER; each coil is independently driven). In this area DTT will complement JT-60SA.

Detached regimes optimization and control by impurity seeding in various scenarios. Simulations show that seeding is necessary for detachment as it happens in ITER and DEMO. Argon provides better performance and allows detachment at full current with $Z_{\text{eff}}=2.8$ and an impurity concentration of 1%. DTT will be equipped with a divertor gas injection system, which is traditionally used in tokamaks. As a risk mitigation strategy, DTT shall investigate alternative actuators and qualify their requirements during detachment control and during ramp-up. Candidate technologies are supersonic molecular beam injection and micro shattered pellet injection (SPI), a novel first-of-a-kind approach. X-Point Radiator configurations have also been simulated, and can be reached with impurity concentration $\sim 2\%$ [5,6]

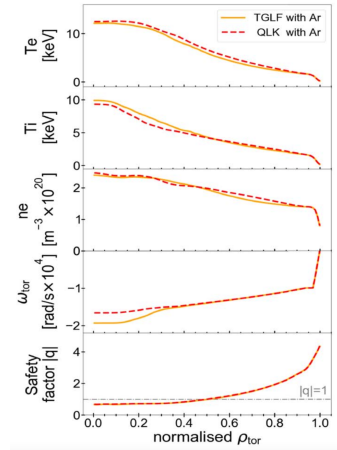


FIG. 3. DTT baseline scenarios (from Ref.[3])

Scaling of λ_q at high toroidal field. DTT will be instrumental to pin down the crucial scaling of the power decay length at the plasma edge, λ_q . DTT can reach a fully integrated scenario where high core performance - with low pedestal collisionality and high density - goes along with edge parameters relevant for the next generation fusion devices.

Development of small/no ELMs scenarios and their control, and control of off-normal events. High-field, high-current ELM control with a variety of techniques will be done in DTT. Moreover, ELM-free regimes will be explored. DTT will be equipped with a SPI Disruption Mitigation System similar to that in ITER, which will be discussed together with the simulation results in this field.

Wall erosion, W migration, D retention and removal studies and assessment in view of application to DEMO. The actively cooled tungsten first wall and divertor, associated with the long discharge duration will allow understanding the impact of tungsten impurities and wall erosion/redeposition on plasma performance. Extensive testing with the Divertor Test Modules for new first wall and divertor materials will be done.

Transport, MHD, Energetic Particle physics studies with reactor relevant dimensionless parameters. One of the main focuses of the DTT research mission is to study the power exhaust problem taking into account core-edge integration across different plasma shapes at ITER and DEMO relevant parameters. In these conditions, Energetic Particles will be produced in DTT through various methods, such as NBI and ICH. Energetic particles will interact with Alfvénic fluctuations, including Toroidal Alfvén Eigenmodes (TAEs) and Energetic Particle Modes (EPMs), among others. Because of the weak Kadomtsev scaling approach considered in designing the device [7] supra-thermal ions will be characterized by typical dimensionless orbit widths, comparable with those of burning fusion plasmas and generally smaller than in present-day devices. Furthermore, the ratio of supra-thermal ion speed to the Alfvén speed in DTT is designed to mimic ITER, ensuring that the strength of energetic particle drive of Alfvénic fluctuations via wave-energetic particles resonant interactions is preserved. Finally, the spatiotemporal cross-scale couplings between core turbulence and Alfvénic fluctuations is preserved. Due to the nature of reactor-

relevant plasmas, which are complex, self-organized systems where diverse elements are tightly linked and necessitate appropriate description, the preservation of these physics with the corresponding spatiotemporal scales stands as a matter of paramount importance for the DTT scientific mission.

3. TOKAMAK SYSTEMS

The DTT tokamak area encompasses most of the components to be installed in the experimental hall, along with their power supplies located outside [8]. The tokamak is designed to reach full performance quickly, with all water-cooled in-vessel components installed from the first day of operations. This approach limits major in-vessel updates but complicated the design of the remote handling (RH) systems, which are critical for the machine's availability and will be used from the initial assembly phases.

Construction has already begun on the superconducting magnet system and its power supplies. The supplies were assigned directly to ensure proper quality assurance. Attention is now shifting to the vessel and out-of-vessel components, while plasma-facing components are completing their design verification before manufacturing.

To ensure operations begin in the early years of the next decade, assembly must be completed quickly. A tender for the assembly process will be launched this year, divided into three phases: final design of procedures and equipment, qualification of processes and personnel training, and the final three-year, two-shift assembly once all components are on-site.

3.1. Superconducting Magnet system

The 18 TF, D-shaped, Nb_3Sn , coils are designed to produce nominally 5.85 T at the major radius in vacuum condition corresponding to a maximum field in the inner leg of about 12 T, very similar to that of ITER. They shall operate in steady state conditions and have been designed to withstand plasma disruptions in any of the three families of reference scenarios (single null, XD, negative triangularity). The procurement of the Nb_3Sn has been completed from Kiswire Advanced Technology Co., Ltd., in Korea, the fabrication of the cable in conduit conductors is on-going by ICAS in Italy and will be completed by the end of 2025. The winding packs are under construction at ASG Superconductors in La Spezia, the same plant used for the fabrication of the ITER TF winding packs. Winding pack production is progressing on schedule and will be completed by the end of 2026. Once manufactured, the winding packs will be stored at ASG waiting for the casing components and subsequent integration activity. Figure 4 shows the WP-02 after the completion of Paschen test performed at ASG premises. The presence of the conducting varnish to create an equipotential surface and the helium inlets on the inner side of the curved leg can be recognized.



FIG. 4. WP-02 exiting the vacuum chamber after the execution of Paschen test.

The contract for the procurement of the casing components, signed with De Pretto industries in Italy, has been started in 2025. With the delivery of the first casing components set at the beginning of 2027, the first TF module will be delivered to DTT site by ASG in the second half of 2027. Last TF will be delivered by the beginning of 2029, in advance with respect to planned assembly in the tokamak hall.

3.2. Vacuum Vessel and outer vessel components

The DTT vacuum vessel represents one of the facility most critical components due to the numerous interfaces with in-vessel and ex-vessel systems that must be managed during the assembly phase and because of the strong stresses it will be subjected to during disruptions in operations. The supply contract is expected to be signed by the end of 2025. The scope of supply consists in two 170° multi-sectors and one 20° sector, all without ports. The port ducts will be supplied separately and installed only after the 360° torus is completed, around which the thermal shield and the toroidal and poloidal field coils will be mounted. From that date, the delivery of the multi-sectors is expected within three years.

The divertor vacuum system design was conducted in collaboration with KIT in Germany and is based on the design for JT-60SA, but with the panels arranged vertically inside vertical ports. This layout provides a pumping capacity of 100 m³/s, which has proven to be adequate for the full-power scenarios considered. The modularity of the system allows the 10 panels to be operated in groups of 3 or 4, 6 or 7, or 10, which ensures the necessary control even in lower-power scenarios with less neutral particle production. The project was completed in 2024, and manufacturing is scheduled to begin in 2026.

3.3. Power supply system

The procurement of TF power supply has been started in parallel to the procurement of the TF coils in 2022. The converters, capable of generating 42.5 kA in steady conditions with 100 V and a current ripple below 0.1 %, have been manufactured by JEMA, Spain, and assembled temporarily in the FCCTF where they will be used to feed the coils during the acceptance tests before the assembly. The Fast Discharge Units (FDUs) instead, made with SiC varistors able to discharge the current linearly in 10 second, are manufactured by OCEM Power Electronics, Italy [9].



FIG. 5. A) Image of the FCCT facility where the DTT TF power supply has been temporarily assembled and commissioned. B) Image of the 27 cabinets manufactured for the 27 independent power supply of the non-axisymmetric coils at EEI.

Only the first FDU of three has been completed and already delivered. Installation in the FCCTF will be completed within 2025 in order to allow the commissioning of the facility in 2026. The remaining FDUs will be manufactured and delivered at later stage. Figure 5a shows an image of the FCCTF where the TF power supply has been assembled and subject to the site acceptance tests.

The design of the power supplies for the PF and CS magnets has been completed and the relative tender will be launched soon within 2025. Being two pulsed systems with a maximum nominal current in the same range of about 30 kA, their designs are similar and are based on the use of supercapacitor units that allow the repetitive charging and discharging during the day limiting the effective electrical consumption from the grid [10].

Finally, the power supply system for the in-vessel coils consists of 32 independent power supplies to ensure maximum operational flexibility for the plant. Three distinct supply contracts were awarded during 2024 as part of the “Next Generation EU program”. The supplies are nearing completion, with delivery scheduled for the end of 2025. Figure 5b specifically shows the cabinets for the 27 power supplies for the saddle coils. These were produced by the company EEI, Italy. Similarly, the power supplies for the axisymmetric divertor and vertical stabilization coils are being completed at OCEM Power Electronics, Italy.

3.4. Plasma facing components

All plasma facing components of the DTT facility shall be actively cooled from the start of operation. The design of the first divertor has been completed [11-12] after a full set of qualification activity carried out both on the plasma facing component design and on the cassette structure [13]. The qualifications of the small mockup of the divertor targets performed in high heat flux testing facility allowed to assess the design choices in terms of W monoblock size [14] and allowed to confirm the capability of the present design to resist to heat load up to 20 MW/m² without any damage at the plasma facing surface and at the joint between the W monoblock and the cooling pipe (see Fig. 6). The activity is now focusing on the fabrication of the full-scale mock-up of the divertor targets using the Hot Radial Pressing (HRP) technique developed in ENEA. This will allow to set-up the fabrication procedures of the 1242 nominal targets of the DTT first divertor whose manufacturing activity will start in 2026. In parallel, also the procurements for the base materials (W monoblock and CuCrZr pipes) are about to start within 2025, as well as the procurement for the fabrication of 54 cassette structures made of 316LN steel.

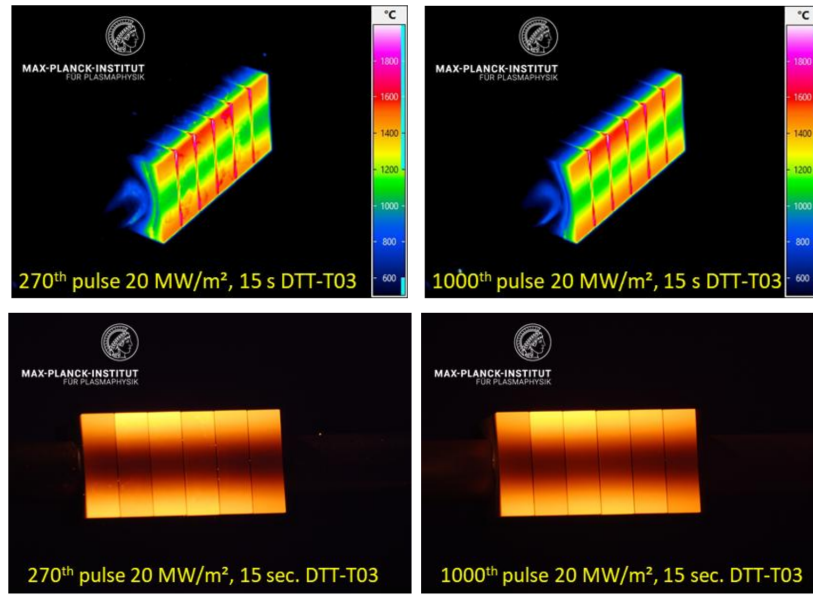


FIG. 6. IR (top) and CCD (bottom) images of the DTT mock-up at the Gladis facility in IPP Garching, after 270 (left) and 1000 pulses at 20 MW/m² with 130 °C of water inlet temperature.

The DTT First Wall has been designed with a poloidal segmentation aimed at preserving the maximum volume of the vacuum chamber to accommodate the different plasma scenarios [11]. It is water-cooled with a total mass flow rate of 380 kg/s at 4 MPa and 60 °C which is able to dispose of 32 MW of power (70 % of the total heating power) with a 20 °C increase in water temperature. Under nominal conditions the mass flow rate is split as follows: 130 kg/s to the Inboard First Wall (IFW), 110 kg/s to the Top First Wall (TFW) and 140 kg/s to the Outboard First Wall (OFW). However, different distributions can be set in order to optimize cooling performance according to operating scenarios. Having completed the design, now the activity is focused on the qualification phase through the use of small mock-up that will be successively tested [15] in linear heat flux facilities before moving to the subsequent manufacturing phase.

3.5. Diagnostics

The design of plasma diagnostics was reviewed in 2024 by an external review panel composed of international experts. The panel produced a priority matrix that has been used to allocate resources. However, the initial conceptual design effort, which involved a total of 77 diagnostic techniques [16], inevitably required considering all systems to ensure their eventual installation. This exercise produced a configuration model, which displays the allocation of diagnostic systems not only on the vessel but also inside the ports. The "port-plug" scheme used in ITER was followed to define the spaces and potential upgrades during the facility's development phases.

The engineering design and procurement phase for the systems is about to begin. The goal is to acquire and lab-test the systems that need to be installed on the vessel before the start of the machine assembly phase in the torus

hall, while the systems to be installed in the port plugs will follow closely behind. In this case, the approach adopted is to assign the coordination of each port plug to the system that has the largest footprint at first plasma.

3.6. Remote Handling systems

When human intervention is no longer permitted due to excessive radiation, the availability of the DTT facility will be ensured through the use of remote maintenance systems. The ability to replace all divertor modules multiple times, to meet specific requests for divertor shape or plasma facing materials, is a key design requirement to be performed in the shortest possible time. To achieve this, DTT is investing significant resources in the realization of Remote Handling (RH) systems, which will be used from the initial assembly phases of the machine. The DTT RH system includes two robotic arms (HYRMAN) for the maintenance of the first wall and the Ion Cyclotron Heating (ICH) antennas, and three Cassette Multifunctional Movers (CMM) for handling the divertor. Furthermore, when the Neutral Beam Injector (NBI) will be installed in DTT, some of the ports dedicated to the handling of the divertor modules will no longer be easily accessible. For this reason, the so-called CTM (Cassette Toroidal Mover) is foreseen, a device that will allow the toroidal movement of the divertor cassettes in the vacuum vessel.

To ensure the effectiveness and reliability of these RH systems, a Remote Handling Training Facility (REMHAT) is being constructed at the CeSMA laboratory of the University of Naples Federico II [17-18]. This facility will play a central role in validating RH tools, RH procedures and equipment compatibility before their deployment in the actual DTT machine and in training the dedicated personnel. The facility is equipped with a full-scale replica of a 110° sector of the DTT vacuum vessel (VV), including mock-ups of the divertor, first wall, and associated piping.

The VV mock-up (Fig. 7a) consists of a portion of the real DTT Vacuum Vessel, and includes 2 RH sectors, equipped with lower port #4 and equatorial port #3 for carrying out operations with the interfaced RH robots. A portion of the upper port #1 is also included. The Vacuum Vessel Support Pads and Support Plates will realize the interfaces with the mockups of the in-vessel components (FW modules and DIV cassettes).

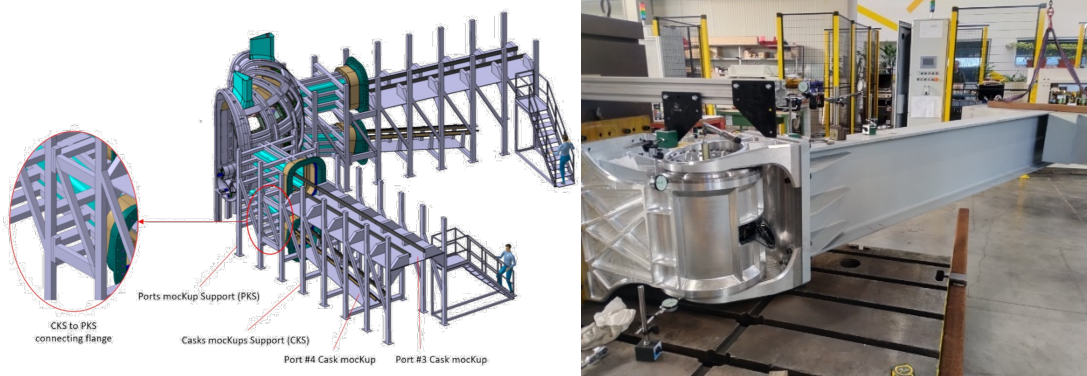


FIG. 7. A) Vacuum vessel mock-up of the REMHAT facility. B) Test of the J2 joint prototype at the OCIMA premises in preparation of the manufacturing readiness review meeting

The HYRMAN is a robotic arm composed of a carrier, a 5 dof planar part and a 6 dof dexterous part. It will have a length of about 6 m and total weight (including the carrier) of about 2 tons. The design requirement for the payload is 350 kg at 100 mm from the TEM (Tool Exchange Mechanism, that allows automatic connection/disconnection of external tools) and 600 kg at 1 m from the last planar joint to insure the handling of the ICH antenna inside the VV through a special gripper. Figure 7b shows the prototype of the joint 2 of the HYRMAN under qualification tests at the contractor premises (OCIMA, Italy) before completing the manufacturing readiness review step envisaged in the supply contract.

3.7. Integration and assembly

The Assembly of the components and the auxiliaries, placed in the Torus Hall Building perimeter, shall be assigned to a qualified firm through a specific tender that is under preparation. The activity shall make extensive use of mock-up to validate the assembly steps, including the training to prototype welding.

The compactness of the machine involves the management of tight tolerances of assembly, applied to heavy and large components. The engineering of the methods and of the tooling, associated with the monitoring of metrology for alignment and reverse engineering operations will guarantee the achievement of the high-quality results required. The Assembly Contractor will guarantee the compliance of the work-flow, to the requirements, assuring the continuity of operation of the relevant skill personnel, particularly involved in special process, prototype activities and in training received from DTT. The contract will be divided in four main steps: i) the engineering phase during which the assembly tooling will be designed in detail; ii) the procurement of the tooling and materials; iii) the qualification of the special process; iv) the assembly of the machine in the experimental hall. According to the previous plan and thanks to the availability of all components at the DTT site at the start of the assembly phase, the assembly time up to the integrated commissioning is estimated in less than 30 months with 20% of contingency assuming 2 shifts per day and a shift on Saturdays particularly for testing activities.

4. HEATING AND CURRENT DRIVE SYSTEMS

The heating combination foreseen in DTT is similar to that of ITER. In its final configuration the DTT additional heating systems will deliver up to 45 MW power to the plasma, by a composition of ECH, ICH and a negative NBI, installed step by step from phase 1 to phase 3 of the DTT plasma operations [19]. The choices in the realization of these systems are based on a trade-off for minimization of new development and the fulfilment of the challenging requirements to reach the task assigned to the plasma heating systems. In the first phase DTT will be equipped with half of the power foreseen (in total) for the ECH and ICH systems, 14.4 MW and 3 W to plasma respectively. The 10 MW of negative ion NBI will be added in the second phase, while the completion of the ICH and ECH systems is foreseen in the third upgrade of DTT. In the present status the procurement of power generator of the two RF systems is ongoing together with the completion of the design of the transmission and coupling elements, to start the realization in the following 2 years. In the meanwhile, the design of NBI system is going to be completed to begin the engineering phase as scheduled.

4.8. ECH system

The first half of the 32 MW/170GHz DTT ECH system, required for the first phase of operation, is under procurement with the target to have 8 MW installed for the start-up of the machine and its completion within 2 years later [20]. The procurement of the first 16 gyrotrons is ongoing under a contract between DTT and THALES.



Figure 8. a) DTT first Gyrotron manufactured by THALES. b) RF Load tested in factory.

The first gyrotron (Fig. 8a) has demonstrated, during extensive test at FALCON test facility in SPC Lausanne, the compliance with the technical requirements, in terms of power level (1.03 MW), RF power stability and efficiency (about 40%) during the 100 s pulse required for DTT [21]. The conceptual design of the quasi-optical transmission lines has been completed and prototyping activity in the realization of mirrors has been started. The 4 RF loads foreseen for the two cluster (8 gyrotrons each) of the first phase, are under procurement, being the first of them factory successfully tested and close to the final acceptance (Fig. 8b). The design of the launching antennas has reached a maturity level, also facing the challenge to minimize high forces and torques on the mirrors and their supporting structures, that requires the realization of full-scale prototypes to perform comparison between internal

or external (to vacuum) driving mechanism, as possible choices to be done in the next year, before to start the procurement phase.

4.9. ICH system

Also the first two 1 MW Solid State ICH transmitters with frequency spanning in the range 60-90 MHz, that are part of the first ICH module, are under construction, with the final delivery and acceptance test in 2026. The completion of the module with other 2 MW of RF power, will be procured based on the results of this first pioneering procurement. In the meantime, the design of transmission and coupling elements has been advanced [22] to fulfil the DTT requirement in term of power coupled to plasma (1.5 MW per antenna) with necessary control of phase. The RF antenna design has addressed its focus to the optimization of parallel electric field ($E_{||}$), responsible for plasma contamination by impurities during ICRH operations.

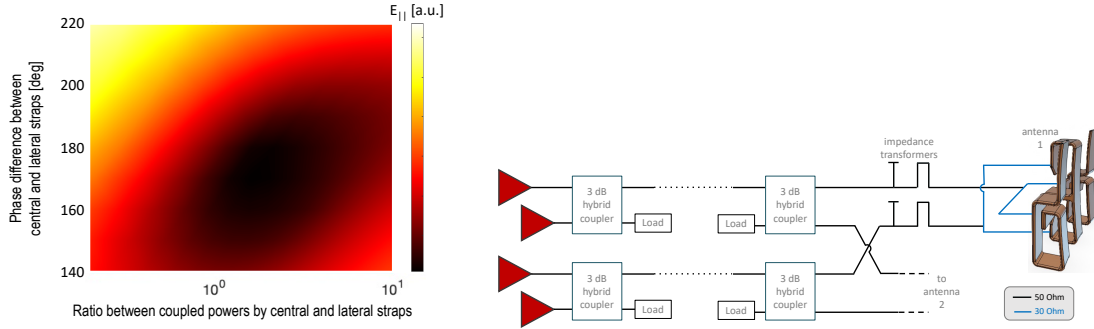


Figure 9. a) Result of the simulation on the parallel electric field in front at the antenna. b) schematic view of the transmission lines of one ICH module.

Figure 9a shows a calculation of such fields in front of antenna limiter, varying the feeding of the central and lateral straps: the minimum of $E_{||}$ is very close to the preferred working conditions, i.e., dipole phasing and same coupled power between central and lateral straps. Figure 9b shows a block drawing of the ICH Transmission Line in which the main matching and combiner elements to transmit and control the power of 4 Solid State Generators to the two 3-straps antennas are reported. Also, part of the transmission line is under procurement, to realize a test bed for transmitter testing. The conceptual design of the antenna is going to be completed in 2016.

4.10. NBI system

The 10 MW/510keV NBI system, planned as an upgrade to be carried out in the middle of the next decade, is presently in the design phase, based on the return of experience gained in the development and test of MITICA injector under realization at the Neutral Beam Test Facility in Padua. The negative ion will be generated in 8 plasma sources driven by RF generators and then accelerated by a sequence of 5 grids up to the target energy of 510 keV.

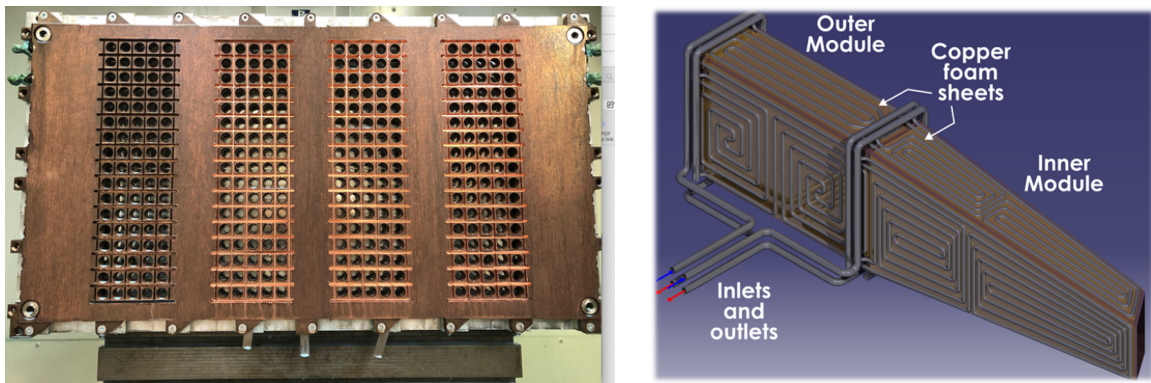


Figure 10. a) full scale extraction grid of DTT accelerator after final machining. b) liner design to protect vessel duct from thermal load due re-ionization

The construction of these grids has been the main subject of the DTT development with the realization of 2 full scale sector of extraction and plasma grids (see Fig. 10a) using the 3D printing techniques that allows more effective cooling channel design and optimized optics for increasing efficiency [23].

An effort has been dedicated to the study of a passive shielding of the beam line component from the poloidal stray field generated by DTT and to the development of a protection of the vessel duct from the thermal load due to the re-ionization (Fig. 10b), occurring when the neutral particles met the D_2 entering in the tokamak. Both the issues have been solved, assuring the required efficiency of the NBI system [24].

5. BALANCE OF PLANT

The DTT (Divertor Test Tokamak) is being built and, while several of the main components are in various stages of manufacturing, now the complex of civil infrastructures and services necessary to host the machine and its auxiliary plants is ready to start construction. DTT largely reuses the former FTU complex but requires also the construction of new buildings and infrastructures (Fig. 11). The design has been completed, having care to integrate all plants and subsystems in an overall 3-D plant integration model using advanced 3-d modelling, to be progressively developed into a full-fledged Product Life cycle Management (PLM) model. Careful analyses of the integration of civil works with the tokamak machine, additional heating systems (ECRH, ICRH and, at a later stage, NBI), electrical and water-cooling systems, cryoplant, assembly facilities, diagnostics and control system, logistics areas are deemed to optimize the concurrent activities and limit changes and rework.

The new building complex, the tender of which has been released in May 2025, features 150 000 m³ of new constructions including the new Tokamak Hall Building, the ECRH Additional Heating Building (ECRH and associated power supplies), the Water-Cooling, Power Supplies and Diagnostic buildings. The erection of these 9 new buildings will be preceded by important excavation (74 000 m³) and soil consolidation activities that will substantially change the current layout and configuration of the ENEA Center in Frascati.

The existing FTU buildings (now fully cleared from previous equipment), after refurbishment, will host all the cryoplant (compressors hall and ACB and RCB), ICH power supplies, facilities for assembly preparation and rehearsal etc. The design was supported by a careful analysis of the applicable urban planning regulations, and the necessary variants and strategies for obtaining all construction permits, were shared with the competent authorities, quickly achieving the objective. Aspects closely related to the specific characteristics of the context and the radiogenic activity were examined in depth, allowing the acquisition of additional specific permits by conducting preliminary investigations essential to the design, such as detailed geological and seismic analyses, environmental studies, archaeological and radiological surveys.

The design of the buildings has been carried out with a focus on minimizing emissions into the environment, ensuring that water resources are not impacted by using a recirculating cooling system and preventing the emission of radiation outside the buildings. A detailed constructability plan has been developed, resulting in a realistic construction phasing, that allows to match the restricted construction space while respecting the constraints of an anthropized area. The plan integrates logistical and accessibility considerations and outlines the site construction organization activities such as excavation, containment structures, new roads and ramps, underground networks and demolition, along with the construction of key buildings. Special focus has been given to the installation of electrical and specialized systems to ensure integration with the infrastructure.



Fig. 11 – Render of new buildings.

The new machine has required a substantial increase of the electrical power delivered to the ENEA Site and for this purpose Terna, the Italian Transmission System Operator, has started the lay down of two new 15 km high-voltage underground lines connecting the main electrical network node of Roma-Est to a new 150-kV grid switchyard close to ENEA Center. From this new switchyard, an underground cable are going to reach the new DTT substation (Fig.12) where two step-down transformers for pulsed loads with operating power range from 80 MVA up to 110 MVA and two 20 MVA stepdown transformers for the steady-state loads will supply 20 kV to be distributed to 5 substations strategically located in the DTT site to match power demand of 29 MVA Steady State Power and 198 MVA Pulsed Power. Furthermore, to comply with the National Electricity Grid Code, measures will be implemented to mitigate the power factor and guarantee power quality. A new connection to MV Italian National Grid is arranged to supply the construction site and facilities supporting DTT, while maintaining energized all existing power loads of the ENEA Center. The design is complete and ready for tender.

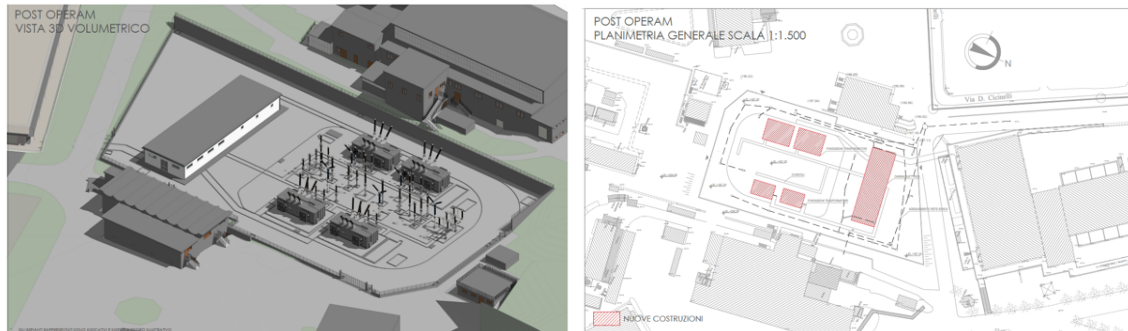


Fig. 12 – New DTT HV substation 3D view and layout

The design of the water-cooling and other utilities systems (i.e. nitrogen and instrument air) has been completed and components have been developed to a level allowing, now, a final phase of detailed design, in which optimization of the assembly inside buildings with restricted overhead and side spaces can be performed to reduce installation times and costs. A secondary cooling water system includes circulation and distribution pumps, chillers, storage vessels, piping and activated water treatment packages. A primary cooling circuit, which serves the divertor, first wall, vacuum vessel, ECH, ICH, power supplies and diagnostics, is composed by circulation pumps, heat exchanges, electric heaters, piping and mechanical filters. Other auxiliary systems, such as instrument air and nitrogen, are also integrated into the design, along with a comprehensive instrumentation and control system. In addition to these elements, the design included the reutilization and complement of existing LN₂ tanks and distribution piping, together with helium storage tanks installation and external cryolines routing.

Logistic studies have been performed for the route allowing main loads, from generic manufacturing sites, either in Italy, Europe or outside Europe, to reach the DTT site, involving multimodal transports (ship, barge, trucks or specialized transport vehicles), roads and bridges reinforcements or temporary block, temporary storage on-route, on-site or ex-site.

While the start of construction activities has been delayed, due to a combination of external factors (mainly the COVID pandemics and results of the geotechnical and environmental surveys) and reorganization of the DTT management, now the project has taken advantage of this time to produce a mature infrastructures design.

6. CONCLUSIONS AND PERSPECTIVES

The DTT project is progressing towards the start of operation. A large support both at national and local level has been gathered as the facility is the largest scientific infrastructure presently under construction in Italy. The main components are under manufacturing. Three toroidal magnetic field winding packs have been completed and tested. The power supplies for the TF have been installed in the Coil Cold Test facility in Frascati and those for the internal coils will be delivered in the first half of 2026. The pre-series ECH gyrotron has been tested and the series gyrotrons are under manufacturing. The first two ICH transmitters are under assembly. Civil works are starting with the demolition of some of the existing buildings and the excavation work for the new buildings is expected to start in September 2026. The present schedule foresees the achievement of the first plasma in 2032 driven by the availability of the new tokamak hall and the assembly procedure. The Research Plan, that has been prepared with the contribution of several scientists from the Eurofusion laboratories, will be continuously updated to reflect the most urgent needs of the programme.

DTT will be the largest tokamak in operation in Europe apart from ITER in the next decade and will be available to the international scientific community to prepare ITER operations and to investigate advanced solutions for the heat exhaust in a fusion power plant.

REFERENCES

- [1] ROMANELLI, F., Divertor Tokamak Test facility project: status of design and implementation, Nucl. Fusion **64** (2024) 112015.
- [2] F. CRISANTI, G. GIRUZZI, P. MARTIN et al., Divertor Tokamak Test Facility Research Plan, Version 1.0, May 2024, <https://www.dtt-project.it/index.php/about/dtt-research-plan.html>
- [3] CASIRAGHI et al 2023 Plasma Phys. Control. Fusion 65 035017
- [4] MARIANI A. et al., Nucl. Fusion **64** (2024) 106024
- [5] BALBINOT L. et al, Nuclear Materials and Energy 27 (2021) 100952
- [6] BALBINOT L. et al., Nuclear Materials and Energy 42 (2025) 101835
- [7] VARIOUS AUTHORS Special Section of Fusion Engineering and Design Vol. 122, 2017, 253-294
- [8] POLLI G.M. et al., “The Divertor Tokamak Test Facility: machine design, construction and commissioning”, This Conference
- [9] GALVIN T., et al., “Characterisation of SiC Varistors at Ambient and Elevated Temperatures for Protection of Superconducting Magnet”, IEEE Transactions on Applied Superconductivity, (2024) 34 (3), pp. 1 – 5.
- [10] PIPOLO S., et al., “Supercapacitor bank design for the DTT Central Solenoid power supplies”, Fusion Engineering and Design, Volume 216, July 2025, 115074.
- [11] BALBINOT L. et al., *Defining operational scenarios for DTT in-metallic environment: a modelling study of core-edge dynamics and plasma-wall interaction*, This Conference
- [12] INNOCENTE P. et al., *Design of a multi-configurations divertor for the DTT facility*, Nuclear Materials and Energy, vol. 33, no. 101276, 2022.
- [13] GIORGETTI F., et al., *Qualification Activities for the DTT Divertor*, IEEE Transactions on Plasma Science, 2024, DOI: 10.1109/TPS.2024.3384010.
- [14] ROCCELLA S., et al., *Armor Thickness Assessment for the Divertor Tokamak Test Facility (DTT) Divertor Targets*, IEEE Transactions on Plasma Science, 2024, DOI: 10.1109/TPS.2024.3404135
- [15] FURNO PALUMBO M. et al., Status of design and manufacturing qualification activities of the first wall of the Divertor Tokamak test facility, Fusion Engineering and Design, Volume 222, 2026, 115435.
- [16] TENAGLIA G. et al., *Functional Analysis for the diagnostic systems to support the exploitation of the Divertor Tokamak Test facility*, Fusion Engineering and Design, Volume 170, September 2021, 112692.
- [17] ZOPPOLI A., BUONOCORE S., DI GIRONIMO G., IEEE Transactions on Plasma Science, (2024) 52 (9), pp. 4082 – 4089.
- [18] DI GIRONIMO G., et al., Fusion Engineering and Design, (2023) 195, art. no. 113978.
- [19] GRANUCCI G. et al, *The Status and Design Challenges of the Heating and Current Drive Systems for DTT* - This Conference
- [20] GARAVAGLIA S. et al, *Overview of the Design And Procurement of ECRH System for DTT*- This Conference
- [21] GARAVAGLIA S. et al, *First RF operations of the gyrotron for the DTT ECRH System*- submitted to FED .
- [22] CECCUZZI S. et al *Progress in the development of the ICRF system of DTT, FED*, vol. 213, p. 114849 (2025), doi:10.1016/j.fusengdes.2025.114849.
- [23] AGOSTINETTI P. et al “Innovative concepts in the DTT Neutral Beam Injector” IEEE transactions on plasma science, vol. 52, no. 9, september 2024
- [24] VERONESE F. et al “Performance optimization of the electrostatic accelerator for DTT neutral beam injector,” IEEE Trans. Plasma Sci., vol. 50, no. 11, pp. 4033–4038, Nov. 2022.