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The DTT device: Safety, fuelling and auxiliary system

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HIGHLIGHTS

- The assessment of the radiation fluxes, loads and radiation damage is crucial in the design of the DTT machine, as a significant neutron yield by D-D reactions is expected.
- Concerning safety, an accurate shielding assessment is necessary to effectively the design DTT building.
- Fuelling and pumping are crucial for plasma production but at the same time are relevant in the licensing assessment for a radiogenic device.
- DTT is a superconductive long pulse devise that needs that most of the components inside the vacuum vessel are actively water cooled.
- The cryostat plays an important role because it forms part of the secondary confinement barrier.

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ABSTRACT

Apparently miscellanea of arguments are discussed in this paper but nevertheless all them are strictly related to safety of the DTT project. DTT should operate integrating all the reactor relevant physics and technology features, e.g. significant power loads, flexible divertors, plasma edge and core conditions approaching those of DEMO. The licensing process is discussed in the framework of the Italian law for which DTT will be classified as a radiogenic machine of category A. The guidelines for neutronics, fuelling and pumping issues are highlighted. Finally, the cooling systems and the cryostat project are also illustrated.

1. Introduction

One of the key issues in making fusion an affordable energy source consists in developing all the necessary tools to handle the huge amount of thermal power originated in fusion reactions. Efficient power exhaust handling is needed for guaranteeing to the future fusion reactor the necessary competitiveness in terms of energy cost. The European Fusion Road Map [1] dedicates one of its missions – the number 2 – to solve this critical aspect.

The Divertor Tokamak Test facility (DTT) has been envisaged to tackle this major challenge, entailing the development of a power exhaust system able to withstand the large thermal loads expected in DEMO, the first fusion power plant to be built around 2050.

The main design parameters of DTT, are: a major and minor radius of 2.15 and 0.70 m, respectively; an elongation of 1.6-1.8; a toroidal magnetic field of 6 T; a flat top duration of the order of 100 s. DTT should operate integrating all the reactor relevant physics and technology features, e.g. significant power loads, flexible divertors, plasma edge and core conditions approaching those of DEMO. In order to meet the requirements for DEMO within the required timescale for its construction, the DTT device has been defined on the basis of a trade-off analysis of the main parameters. The machine has been designed to have the capability to test several different magnetic divertor topologies, in reactor relevant regimes, and different plasma facing materials and configuration, including tungsten and liquid metals. The final target of the experiment is the

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realization of an integrated solution for the power exhaust in view of DEMO.

This paper is included in the Special Issue of Fusion Engineering and Design on the DTT proposal. More details about the machine parameters as well as the scientific goals can be found in the other papers of the issue.

In the project of a device like DTT, the issues of safety and licensing play an important role that can have a strong impact on a number of design choices. In the case of DTT, this impact should be minimized because the site chosen is the Centro Ricerca ENEA Frascati where are actually running two licensed devices: FTU (Frascati Tokamak Upgrade) and the Frascati Neutron Generator.

Although DTT is a machine operating without tritium, the assessment of the radiation fluxes, loads and radiation damage is a crucial design issue, as a significant 2.5 MeV neutron yield by Deuterium-Deuterium (D-D) reactions is expected. Therefore an accurate shielding assessment is mandatory for the design of main hall; in addition the neutron-induced radioactivity, although not critical, calls for a careful consideration from several points of view, including licensing, maintenance, and decommissioning, as well as waste management.

Fuelling and pumping could be also relevant in the licensing assessment, due to possible release on the atmosphere of small tritium quantities produced by D-D reactions. DTT is a superconductive long pulse device; as a consequence most of the components inside the Vacuum Vessel (VV) have to be actively cooled. Therefore possible leaks should be taken into account as well as the cryostat behaviour that forms part of the secondary confinement barrier.

The paper is organized as follows. Safety and licensing are illustrated in the next section. Neutronics are discussed in Section 3, fuelling and pumping in Section 4 and, finally, cooling system and cryostat are presented in Section 5.

2. Safety and licensing

The safety analysis will start from the identification of the (nuclear and conventional) hazards in the plant and their relevant characteristics (neutron flux, inventories and mobilization factor, etc.). The radioactive source terms in DTT are:

- the neutrons produced during the plasma phase;
- the activated material of the Poloidal Field Coils
- the Activate Corrosion Production (ACP) in the cooling circuits;
- the activated dust produced by plasma-wall interaction in the VV (particularly during the plasma transients and disruption);
- the small tritium amount in the VV, in the pumps and fuel cycle generated by the reaction D-D.

The neutronics and activation analyses (see next section) identify, characterize and quantify the radioactive source terms. From a first extrapolation from the present machines (e.g. FTU and JET), the radioactive inventories are to be limited and very little mobilized in accidental conditions. The safety functions necessary to control neutron flux and radioactive inventories, to limit the doses to the staff and the releases to the environment in normal and accidental conditions, are relevant for the access control to the tokamak building (during operation) and for the confinement of radioactive material. During the operations the tokamak hall will be slightly depressurized. Finally the Structures, System and Components (SSCs) implementing those safety functions will be recognized with the relevant characteristics to be implemented during their entire life cycle: design fabrication, assembling, commissioning, test, operation, and maintenance. The energies, that in case of accident, can mobilize such radioactive inventories, are the following:

- the magnetic energy (the dominant one is the Toroidal Field (TF) magnetic energy, in the order of 0.7 GJ):, in case of quench, if not discharged, it can generate an electrical arc that might damage the VV or/and mobilize the activated material;
- the cryogenic fluids, particularly the 4k He in the TF magnets (few hundred kg): in case of loss within the tokamak building, the consequent pressure due to He expansion could challenge the leak tightness of the building that constitute the secondary confinement;
- the other coolants present in the plant with the associated enthalpies.

Non-nuclear risks with potential impact on personnel are also identified and adequate protection provisions adopted.

The licensing process will be an up-grade of the already authorized site of ENEA Frascati where radiogenic systems are currently operated in Frascati Tokamak Upgrade (FTU), Frascati Neutron Generator (FNG) and Proton Accelerators [2–4]. This will facilitate and speed up the procedure.

The licensing process should not have negative impact on the time schedule. DTT will be classified, according to the Italian law, as a radiogenic machine of category A; as a matter of fact, DTT will produce a neutron yield greater than 10^{17} n/s all over the solid angle averaged with time. A machine classified in category A, according to reference, needs a licensing permit from the Industry Minister. The Licensing Procedure is summarized in [5].

The request of licensing to construct and operate DTT has to be accompanied by the following set of documents:

- description of the installation plant and systems;
- suitability of the area, buildings and structures;
- radioprotection structures and organization;
- operation program and procedure;
- qualification of personnel;
- operation domain including possible foreseeable extensions;
- accident analysis and relevant consequences with reference to the operation domain and to the external and internal possible events;
- radioactive wastes assessment and management.

The Ministry of Industry, once the authorization process is finished with the positive opinion of all the ministries and organizations involved, will issue the licensing permit for construction and operation, accompanied by possible specific prescriptions relevant to design, construction, commissioning, operation, test & maintenance and decommissioning of DTT. The construction can proceed in parallel to the licensing process. To begin the normal operations, after the integrated commissioning phase, the DTT plant has to be included in the local emergency plan, under the responsibility of the Official representing the central government in that area. It is worth mentioning that the Frascati ENEA Research Center has been already licensed for the operation of FTU that has radiological effects very similar to DTT; as a matter of fact, the FTU license provides the possibility of some shots with tritium assuming an ionic temperature of about 7 KeV, i.e. a neutronic production close to that foreseen for DTT. The valuable experience gained by ENEA team since the past three decades in the operation of similar devices is a good guarantee for the timely and successful conclusion of the process. In Fig. 1 the authorization process and the involved authorities are described in details.

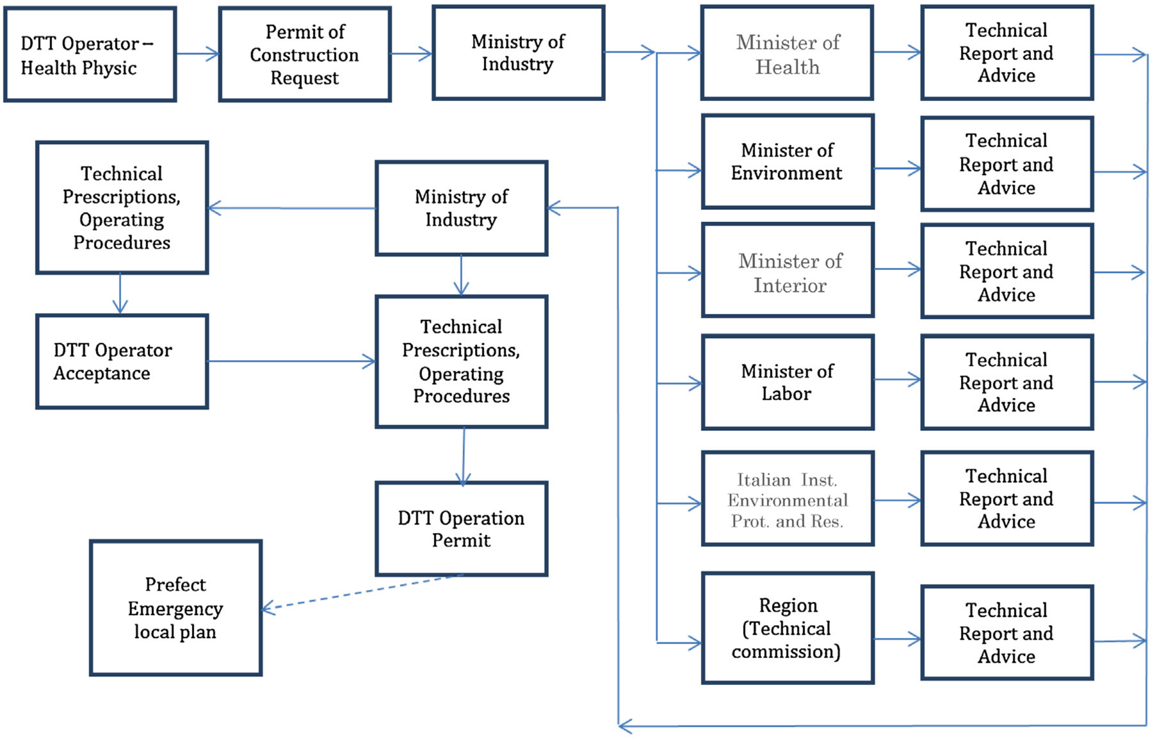


Fig. 1. DTT Licensing Scheme.

3. Neutronics

Neutronics and activation analyses are fundamental for DTT machine design and for its licensing process and diagnostics assessment. As a matter of fact, although DTT is designed to operate without tritium, a deep assessment of the radiation fluxes, loads and radiation damage is required since a significant 2.5 MeV neutron yield by D-D reactions is expected. Concerning the safety, a shielding assessment is necessary in designing the DTT building; in addition the neutron-induced radioactivity, although not critical, needs careful consideration for licensing, maintenance, and decommissioning, as well as for waste management.

The assessment of the relevant nuclear responses has been performed with the Monte Carlo N-Particle transport code MCNP (Version 5) [6].

The neutron source (neutron emissivity [$n\,m^{-3}\,s^{-1}$] on a poloidal plasma section) foreseen for DTT reference H-mode scenario (peak electron density $n_e = 2.3 \times 10^{20}$, peak electron temperature Te = 11 keV) was calculated using a code specifically developed by ENEA for ITER ((Measurement Simulation Software Tool, MSST) [7]). The source is evaluated for the scenario equilibrium configuration, using the ion temperature profile (T_i), the ion density profile (n_i) and a parameterization of the neutron reactivity in terms of the ion temperature. The list of assumptions includes: constant neutron emissivity on the magnetic surfaces and, in addition, the same electron and ion density ($n_i = n_e$) and temperature ($T_i = T_e$), the total neutron rate (n/s) is evaluated by integration of the neutron source. A neutron rate value of 1.3×10^{17} n/s was obtained for the DTT reference H-mode scenario. It can be noted that such a figure is sensibly higher than the typical yield of current machines operating in DD, but in line with the rate of the modern tokamaks (e.g. JT-60SA).

The evaluation of three-dimensional distributions of neutron and photon fluxes and, in addition, of the effective dose rate for shielding analyses, have been carried-out by using a simplified 360° MCNP model of DTT tokamak, including buildings.

The assessment of nuclear loads on each DTT component has been instead performed using a modified 3-D MCNP model of a 20° toroidal sector (already adopted for the analysis of FAST machine [8–10]) with a detailed representation of DTT layout. In both simulations the D-D neutron source was described by a parametric representation of plasma emissivity and the results of the simulations were normalised to the neutron rate value (1.3×10^{17} n/s) obtained for DTT. Fig. 2 shows the equatorial sections of neutron flux distribution and, in addition, the effective dose rate for H-mode scenario. The maximum neutron flux inside the plasma chamber is $1.6 \times 10^{12}\,n\,cm^2\,s^{-1}$, in the outside cryostat in the order of $4.7 \times 10^{10}\,n\,cm^2\,s^{-1}$ and, finally, close to the building wall it decreases to $2 \times 10^9\,n\,cm^2\,s^{-1}$. The photon flux is about 4 times lower than neutron flux.

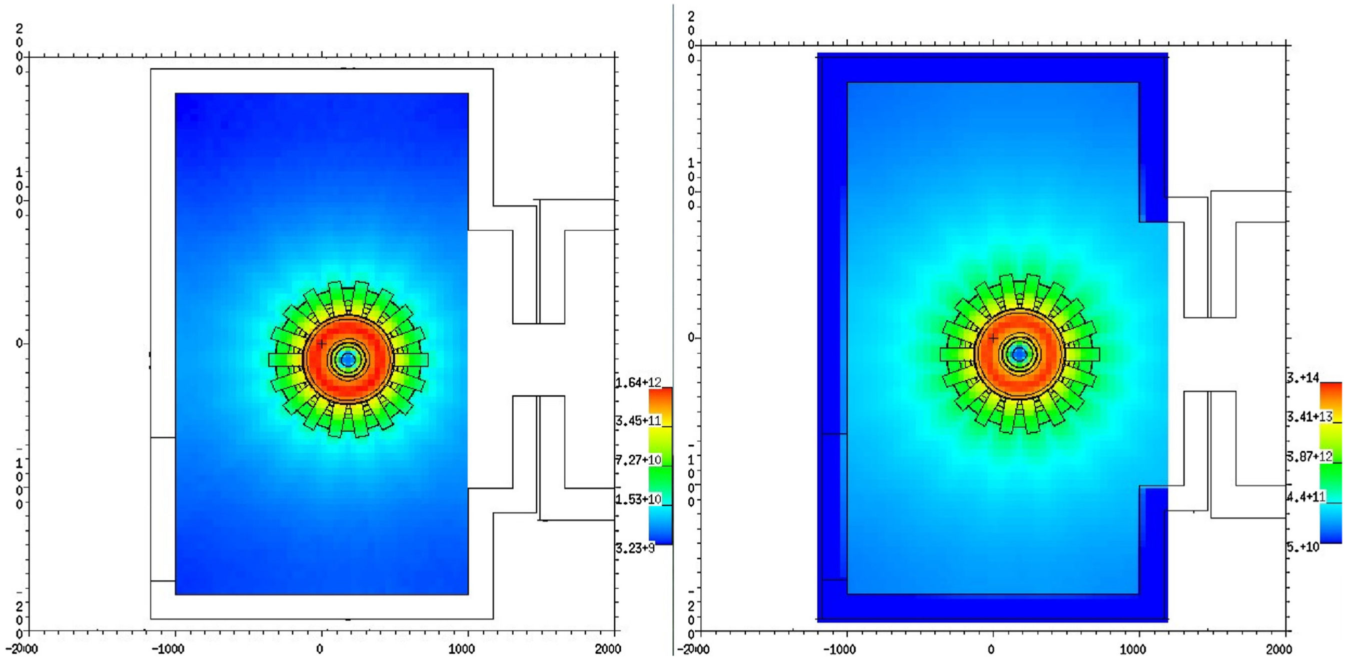
In addition, the nuclear heating density of the first turn of TF coil inboard at the equatorial zone has been performed. This zone has been selected because the higher nuclear loads arise in the equatorial plane and the space available for additional shielding at inboard side is rather limited.

Fig. 3 shows the 20° toroidal sector used as MCNP neutronic model. Reflecting boundary condition has been imposed to model the full extent of the machine.

The effective dose rate varies between 2500 Sv/s inside the plasma chamber to 0.01 Sv/s on the top corner below the ceiling; it is mainly due to the neutrons (the secondary photons contribute to a few percent of the total).

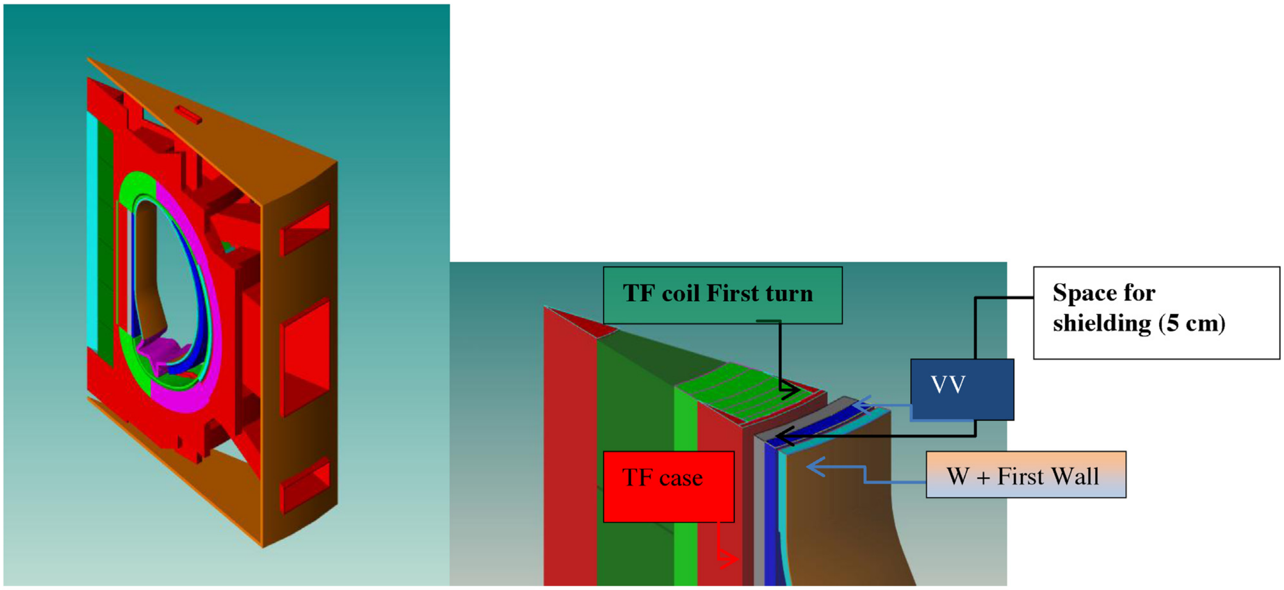
Previous studies have shown that a concrete, 2,20 m thick, bunker wall provides attenuation greater than 6 orders of magnitude [8]. Under these conditions the estimated effective dose rate level outside building during operations will be less than ~0.2 μSv/s.

The shielding has an important impact on the behaviour of each component of the system. The nuclear heating on the first turn of TF coil has been calculated, excluding any shielding on the magnet but including a number of shielding options for the space between the VV and the TF front case (grey zone in Fig. 3). The characteristics



(a) (b)

Fig. 2. Equatorial plot of (a) the neutron flux (n/cm^2/s) and (b) the effective dose rate (pSv/s) maps inside DTT bunker. The dimensions are in cm.



(a) (b)

Fig. 3. MCNP model of DTT used for shielding assessment of TF coil heating (a) and detail of inboard layout (b).

of the analysed shielding configurations and results achieved are reported in Table 1.

The nuclear heating on the TF (in the order of 3.77 mW/cm^3, see option (a) in Table 1) can be reduced by a 5 cm thick shield to a value of 1.26 mW/cm^3 and 2.03 mW/cm^3 with B_4C or a ITER VV-like mixture, respectively. In Table 1 a parametric analysis of the impact of the shield thickness for the B_4C is also reported (options (e)–(h)), as well as the performance of a mixed solution (option (i)).

An active cooling of the casing would reduce the shielding demand on the TF coil heating; a proper shield based on boron carbide might be safely adopted to protect TF coils.

Considering the attenuation capabilities of B_4C and the space actually available between VV and TF case, a total nuclear load on the TF coil in the order of 5–10 kW is estimated. However, by increasing the shielding thickness and adjusting the VV design and/or by slighting reducing the operational density, this figure could be reduced to 2 kW. This is the value assumed as a reference for the design of the TF magnets.

The maximum estimated absorbed dose in the TF insulator is 3×10^{-24} MGy/n on the equatorial midplane. Assuming a design limit of 10 MGy on epoxy, the operations should be limited to a total production of 3.33×10^{24} n. This figure is two orders of magnitudes higher than that expected in the DTT operations; hence, the

Table 1
Nuclear heating density on TF coil inboard first turn.

Shielding configuration		Nuclear heating density (mW/cm^3)
a)	no shield	3.77
b)	5 cm 80%$_{vol}$ SS316 + 20%$_{vol}$ H_20	3.23
d)	5 cm ITER VV-like mixture[a]	2.03
e)	5 cm B_4C	1.26
f)	4 cm B_4C	1.45
g)	3 cm B_4C	1.68
h)	1 cm B_4C	2.32
i)	2 cm 80% $_{vol}$ SS316 + 20% $_{vol}$ H_20 + 3 cm B_4C	1.34

[a] H20 41.0%, SS304B7 36. 9%, SS316L(N)-IG 15. 9%, Ti-6Al–4 V 1. 9%, Inconel 625 0.5% vol and CuNiBe, 0.4% (volume%), the remainder is void.

Table 2
Fluxes, nuclear heating and damage on tungsten PFC in inboard midplane.

Nuclear quantity on W-PFC inboard	Value
Total neutron flux (n cm^{-2} s^{-1})	9.1×10^{11}
Fast neutron (E> 0.1 MeV) flux (n cm^{-2} s^{-1})	7×10^{11}
Gamma flux (γ cm^{-2} s^{-1})	2.4×10^{11}
Nuclear heating density (mW/cm^3)	50
Damage (dpa/s)	7.3×10^{-10}

maximum dose in the insulator at the end of operations is expected well below the limit recommended for the replacement.

On the basis of previous studies [9], the estimation of the neutron and gamma fluxes, nuclear heating and dpa on Plasma Facing Components (PFC) and, in addition, of the neutron induced activation has been performed as well.

Concerning the nuclear loads on PFC, the results on W-layer in inboard midplane are summarized in Table 2. In outboard equatorial zone the expected values are 10–20% higher. In this zone, the total neutron flux is of the order of 10^{12} n cm^{-2} s^{-1} and the fast neutrons contribution is about 80% of the total. The ratio between gamma (generated by neutrons) and neutron flux is about 0.25. The nuclear heating on W is mainly due to gamma (98%). The damage on W at the end of DTT life is expected to be lower than 2×10^{-4} dpa; therefore the radiation damage can be neglected.

The radioactivity induced by neutrons has an impact on maintenance operations and waste management.

A not negligible activation at short-medium times after DTT shutdown is expected especially in plasma-facing components. The estimated contact dose rate level at 1 days at the end of DTT operations is indeed ~100 mSv/h in tungsten. At longer cooling times, higher induced radioactivity is observed in steel mainly because of nickel, cobalt, and tantalum activation (i.e. ~10 mSv/h in VV at one month after shutdown); therefore a suitable remote handling is mandatory. The radioactivity level may require the preparation of an ad hoc temporary repository to store some of the dismounted activated components However, within 50 years from the shutdown, the contact dose of all components is expected to be <10 μSv/h. This level indeed, these can be classified as low level waste, being the specific activities lower than 5 MBq/g for short-life radionuclides and 40 kBq/g for long life isotopes of Nickel and 400 Bq/g for long-life nuclides according to the Italian regulation [11].

Outside the cryostat, the shutdown dose rate level and the concentration of ^{41}Ar and ^{13}N from air activation depend on several causes, including: port arrangement, design of vacuum vessel, shield and cryostat, as well as materials chemical compositions.

With optimized shielding design, the shutdown dose rate level outside cryostat could be reduced to ~10 μSv/h after one week at the end of the DTT operations. Under these conditions, hands-on operations would be possible for external components; however the access to the torus hall should be in any case controlled and maintenance operations accurately planned, to ensure that the annual exposure level will be well below 20 mSv to comply with Italian regulation [5].

The problem of activation of air can be solved by filling boron-doped concrete in the wall of the cryostat and by adopting a suitable ventilation and air conditioning system of the experimental building.

4. Fuelling and pumping

As typical for any Deuterium operated device, the DTT design gives a particular emphasis in both the central fuelling and the divertor fuelling with the aim to optimize the radiation in that region.

The fuelling system includes the following main sub systems:

- Deuterium (and Hydrogen) plasma fuelling based on valves and pellet injector, mainly positioned in the mid-plane;
- local neutral density control in front of the ICRH antennas;
- noble gas impurity injection in both the main plasma and the divertor region;
- massive gas injection in the main plasma region for disruption mitigation in different poloidal and TF coils location.

The gas injection required for both H2/D2 and impurity injection, excluding massive gas injection for disruption mitigation, is in the order of 200 Pam^3/s.

Mass spectrometer stations are used to monitor the residual gas and to detect vacuum leaks.

The number of pumps needed for evacuating the DTT vacuum chamber, depends on the total area of DTT vacuum chamber, including ports and ICRH antennas has to be defined.

By allowing for the specific INCONEL 625 vacuum vessel and first wall (the W coated part of the latter giving a minor contribute) outgassing rate, after all cleaning procedures, of 6.7 10^{-9} Pa m^3 s^{-1} m^{-2} at 100 °C, corresponding, for the area of about 200 m^2, to a total outgassing rate of about 1.3 10^{-6} Pa m^3 s^{-1}, the effective pumping speed, needed for pumping the torus down to P = 1.33 10^{-7} Pa, can be calculated, from S_{eff} = out. rate/P, to be about 10 m^3 s^{-1}.

The conductance between a pump, located at the equatorial plane, and the vacuum chamber can be supposed dominated by the conductance of the pipe between the pump and the port. In fact, a realistic conductance of such a pipe, for a turbomolecular pump with pumping speed S = 1.5 m^3 s^{-1} is about 1.1 m^3 s^{-1} (T = 300 °K, M = 29 (air)) and a molecular regime have been considered, while the conductance of the equatorial port is for sure much larger. Then the overall required number and the pumping speed can be calculated taking into account both required effective pumping speeds and conductance values. The calculation of real conductance is carried out with the available ad hoc codes, starting from the exact geometry of the duct regions and, in addition, assessing if, in the pumping ducts, transitional flow regimes (intermediate between molecular and viscous flow regime) are to be taken into account.

An innovative alternative is included in the design of the pumps to be installed in DTT (not only for divertor area): (i) for the vacuum pump stage, the mercury driven liquid ring pump and (ii) for the high vacuum stage, a combination of mercury diffusion pump and non evaporable getter pump that are under development in DEMO for both Divertor and NBI. This option has many advantages and, in addition, overcome the drawbacks of cryogenic pumping systems: costs (both for investment and running), safety (explosion), availability (frequent regenerations) and maintenance costs.

5. Cooling system and cryostat

Due to the long pulse duration, many DTT systems require to be cooled during the shot. In most cases, the cooling water should

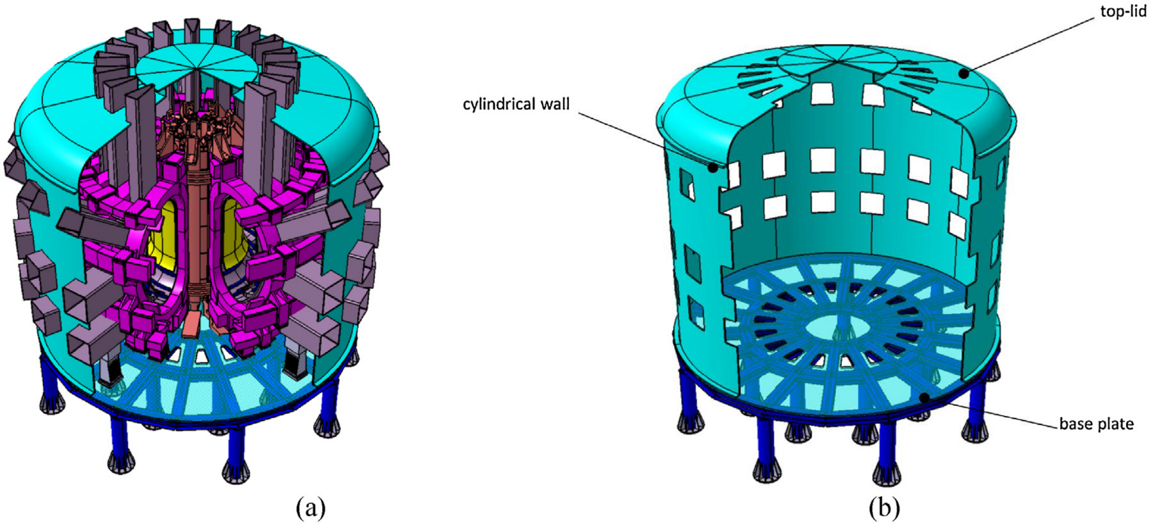


Fig. 4. The DTT Cryostat Vessel: (a) ports and penetrations; (b) vessel elevation view.

be demineralized; as a consequence, a closed water loop with exchange heat system is required.

The design foresee that most of the subsystems will need an own cooling water system with relative pumps, tubes, heat exchangers, sensors and local/remote control system. However the elements inside the cryostat and in the main hall are supposed to be supplied with a unique circuit, while the ECRH and ICRH plants will each have their own cooling circuit. A power in the order of 200 MW is expected to be dissipated for each shot, corresponding to a total request of about 2000 l/s of which 500 l/s each for ECRH and ICRH. Due to the long duty cycle (one shot lasting 100 s each hour at full power), instead to install evaporative tower, the cheaper solution of a small pools (approximately 5 × 5 × 2m) can be adopted to dissipate the heat.

The heat loads in the magnetic system have been also analyzed. Depending on the operating condition, they can be summarized as:

- in the steady state condition they are mainly due to the radiation, the conduction through the support structure and current leads, the Joule-heat in the conductor joints and terminations;
- during operation, they are mainly due to the nuclear thermal heat, the eddy current losses in the massive support and the AC losses in the conductors due to electromagnetic variations.

The worst thermal condition for the magnet system in the reference scenario is found at the end of Plasma Phase. It is worth noting that the shielding from neutrons and secondary gamma is considered to be capable to keep the heat deposition in the 18 TF coils below a maximum value of 2 kW. The cooling temperatures of each component will be different, but they can be grouped in order to use a single He refrigerator able to provide 3 different outlet temperatures: 4.2 K, 20/50 K and 80 K. However for the components at 50 K and 80 K the refrigeration with He could be also replaced by refrigeration with Liquid Nitrogen, possibly adopting a cryoplant pre-cooled by this refrigerant. A rough estimation of the necessary refrigeration mass flow rates is reported in Table 3.

Table 3
Mass Flow Rate.

COMPONENT	Tin/Tout (K)	Flow rate (g/s)
18 TF coils	4.5/6.5	18 × 14
CS coil	4.5/6.5	52 × 1.5
PF coils	4.5/6.3	60
Current leads	50/300	18 × 1.5
Cryostat Thermal Shield	80/100	45

The refrigeration system design is based on standard refrigerators available on the market. In these machines, low pressure He gas is compressed in an oil screw compressor and, after purification from oil contaminants, it is fed to the cold-box. The cold-box is equipped with counter flow heat exchanger and turbo-expanders. The high pressure (HP) gas is cooled down by returning cold low pressure gas. The HP gas is further cooled by expansion in the turbo-expanders and liquefied by Joule-Thompson valve. Intermediate helium gas outlets are foreseen on the heat exchanger for the 20 K/50 K and 80 K. The power required by the cryogenic plant to prevent the thermal quench of the magnets during operation can be estimated in 4.7 kW@4.5 K (390 g/s) + 72 kW@50 K (30 g/s) + 4.5 kW@80 K (45 g/s); this means that the cryogenic plant shall be designed to supply an equivalent power of about 8 kW@4.5 K.

The Cryostat Vessel (CV) is a vacuum tight container, surrounding the entire Tokamak Basic Machine, which provides the vacuum for the superconducting magnets and forms part of the secondary confinement barrier. The vacuum environment is intended to prevent excessive thermal loads to the components operating at cryogenic temperatures by gas conduction and convection.

The design of the CV has been carried out according to the needs of cost minimization and functionality. It is a single-wall cylindrical vessel, with a vertical axis, a flat base and a tori-spherical top lid (Fig. 4).

The CV is provided of ports and penetrations to the VV.

The CV includes a suitable number of stainless steel bellows to compensate for differential movements.

CV also provides openings for pipes connecting equipment outside the Cryostat to the corresponding elements inside the Cryostat (e.g. magnet feeders, water cooling pipes, instrumentation feedthroughs, CV pumping systems).

CV has been designed in such a way to allow maximum feasible personnel access inside the cryostat, during the preliminary and first operational phases. Then the same access are used for the remote handling operations.

The structure will be designed for an internal pressure of 1×10^{-4} Pa.

The Cryostat has been designed and will manufactured according to the ASME, section VIII-Div.2 as a reference code [12].

The top lid has a tori-spherical shape, about is 1.5 m height and 27 tons weight. The cylindrical section is bolted by flanges to top lid wall at top and to base plate at bottom. Its external diameter (∼10 m) is determined by the size of the TF coils with an additional small radial clearance of approximately 800 mm to facilitate the installation of components and to guarantee proper access space for maintenance. The cylindrical section is about 7 m height; this dimension is suited to allocate the inside components and, in addition, to provide adequate vertical space for the interconnections with external systems. The weight of cylindrical portion of the CV is about 60 tons. The cryostat walls are provisionally dimensioned as 40 mm thick, while the stainless steel base plate is 60 mm thick; however a further assessment is foreseen.

6. Conclusions

Some important aspects in the design and construction of the DTT facility have been presented. In particular the safety aspects and the crucial licensing procedure have been illustrated in the framework of Italian Legislation. In addition the neutron shielding for the superconductive magnets as well as the refueling and pumping have been discussed. Finally the cooling system and cryostat have been illustrated with special emphasis to water needs and the dimensioning of the cryoplant.

Acknowledgements

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