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DTT - Divertor Tokamak Test facility: A testbed for DEMO

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ABSTRACT

The effective treatment of the heat and power exhaust is a critical issue in the road map to the realization of the fusion energy. In order to provide possible, reliable, well assessed and on-time answers to DEMO, the Divertor Tokamak Test facility (DTT) has been conceived and projected to be carried out and operated within the European strategy in fusion technology. This paper, based on the invited plenary talk at the 31st virtual SOFT Conference 2020, provides an overview of the DTT scientific proposal, which is deeply illustrated in the 2019 DTT Interim Design Report.

1. Introduction

In 2012, the European Roadmap to the realization of the Fusion Energy [1] has proposed eight missions specifically aimed to face with the main challenges towards the realization of Demonstration Fusion Power Plant (DEMO) [2]. Mission #2 is focused to develop a heat and power exhaust system able to withstand the large loads expected in the divertor of a fusion power plant.

A specific activity is in progress to optimise a conventional divertor based on detached conditions to be tested in ITER [3]. However, to prevent the negative effects on DEMO of possible unforeseen, technical or technological difficulties, the possibility to design a dedicated Divertor Tokamak Test (DTT) facility has been proposed in the roadmap. Aim of DTT is to assess a set of possible alternative solutions for DEMO, including advanced magnetic configurations and liquid metal divertors.

In 2015 the DTT proposal [4], worked out by an International European Team of experts, has demonstrated the possibility to set up a flexible and effective facility able to bridge the power handling gaps between the present-day devices with ITER and DEMO experiments. More recently, in 2018 the EUROfusion Roadmap [5] has confirmed the role of the DTT device, in Fig. 1, '*as a joint European collaboration*' to tackle the power exhaust problem.

The project is managed by a DTT legal entity composed by ENEA (74 %), ENI (25 %), CREATE (1%). Moreover, formal participation requests have been received by important Italian research centres and universities, such as CNR, INFN, RFX consortium, Tuscia University, Milano Bicocca University, Politecnico di Torino and Tor Vergata University.

The DTT project is actually terminating its conceptual design phase [6] and the engineering phase is proceeding. In the meanwhile, the first call for tenders have been launched with the strand procurement already terminated and several other contracts in the advanced phase of assignment.

Different overview papers have been published in the last few years to describe the status of the DTT project, such as [7–9]. In the present paper, the more recent version of the DTT device is presented. Indeed, a lot of progresses have been reached in the last years and the main design variations respect to [7–9] have involved:

- the increment of the major radius of the device from $R = 2.10$ m [9] up to $R = 2.19$ m
- the investigation of the DTT compatibility with negative triangularity plasma scenario with the possible consequences on the plasma facing components
- the re-design of a vacuum vessel compatible with the new major radius and able to accommodate the new set of plasma alternative configurations (ACs)
- a new design for the Central Solenoid able to increase the performance of the machine in terms of possible flux swing.

All these aspects are discussed in detail in the following sections. The status of the project, its strengths and weaknesses, the European and international meaning of the initiative, have been discussed in detail the DTT Interim Design Report [6] and in recent papers and posters presented in the Virtual Edition of SOFT 2020 [10–28]. Therefore, this

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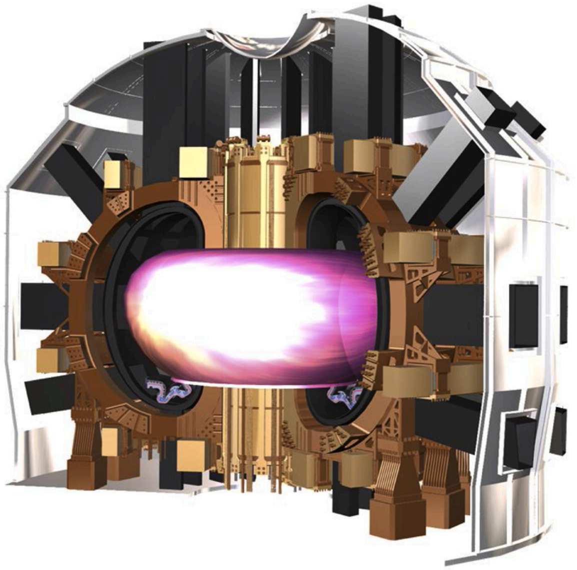

Fig. 1. Sectional view of DTT.

paper is not intended to be exhaustive. It just makes the point of testifying the main aspects of the discussion on the possible DTT contribution to the problem of the power exhaust that animated the Fusion scientific community attending SOFT 2020.

The paper is organized as follows. In Section 2 the main goals of the DTT project are presented together with its main specifications. Section 3 illustrates its main subsystems. Section 4 provides some information about the scheduling of construction and operations. Finally, Section 5 summarizes the status and the perspectives of the project.

2. Project key lines

DTT has been conceived as a flexible test bed capable to tackle plasma exhaust issues in a fairly integrated fashion, according to EU Fusion Roadmap Mission.

2.1. Design guidelines

The main guidelines are here summarized:

I Capability to assess the performance of a conventional divertor:
- with dimensionless parameters similar to ITER and DEMO
- with large values of the parameter P_{sep}/R and very large radiation (up to 90 %), where P_{sep} is the power flowing through the last closed magnetic surface and R is the plasma major radius
- benchmarking the accuracy of the SOL (Scrape-Off Layer) code predictions in ITER and DEMO relevant range of parameters
- testing the effectiveness of closed loop control system of plasma detachment including diagnostics, control algorithms and actuators

II Capability to assess the performance alternative materials and new divertor concepts:
- including liquid metal materials;
- in presence of new or not yet consolidated scenario solutions
- benchmarking the accuracy of the theoretical models used to model SOL, core and LM targets
- testing the effectiveness of a further optimization process to improve the new divertor concepts for selected configurations

2.2. Physical & technological requirements

Table 1
Reference DTT physical parameters.

$n_e(10^{20}m^{-3})$	1.8
n_e/n_G	0.42
$P_{TOT}(MW)$	45
$\tau_E(s)\ H_{98}\ = 1$	0.43
$T_e(keV)$	6.1
$\beta(\%)$	2.2
$\nu^*(10^{-2})$	2.6
$\rho^*(10^{-3})$	2.9

Table 2
PF Comparison among DTT, ITER and DEMO [30] main parameters.

	DTT	ITER	DEMO
R (m)	**2.19**	6.2	9.1
a (m)	**0.70**	2	2.93
A	**3.1**	3.1	3.1
$\mathbf{I_p}$ (MA)	**5.5**	15	19.6
B (T)	**6**	5.3	5.7
Heating $\mathbf{P_{tot}}$ (MW)	**45**	120	460
$\mathbf{P_{sep}}$ **/R** (MW/m)	**15**	14	17
$\boldsymbol{\lambda_q}$(mm)	**0.7**	0.9	1.0
Pulse length (s)	**100**	400	7600

In order to pursue the objectives of the project, DTT fulfils a number of physical requirements, including:

- preservation of 4 DEMO relevant parameters: Te, $\nu^* =$ Ld/λei, λq/λ0, β
- relaxation on normalized Larmor radius: value of (ρi/λq) different, but not very far from that of DEMO,
- integrated scenarios: solutions compatible with plasma performance of DEMO

where T_e is electron temperature, L_d is the divertor field line length, λ_{ei} is the electron-ion mean free path, λ_q is the midplane power decay length in the SOL [29], λ_0 is the neutrals mean free path, β is the normalized plasma pressure. The reference DTT physical parameters, estimated with a 0D approach, are reported in Table 1 and the validation with more refined codes are ongoing.

In addition, a number of technological requirements has been considered, including

- Psep/R $\geq$ 15 MW/m;
- flexibility in the divertor region in order to test several solutions;
- possibility to test alternative magnetic configurations, including X-Divertor, Snowflake, negative triangularity or "long leg";
- possibility to test liquid metals;
- integrated scenarios compatible with technological constraints of DEMO.

2.3. Main design parameters

The DTT project proposes a facility characterized by a major and minor radius of 2.19 and 0.65 m, respectively, with a plasma current of 5.5 MA and a toroidal magnetic field of 6 T. A detailed list of the design data can be found [6]. Here in order to have a direct comparison with ITER and DEMO devices, the main parameters are reported in Table 2.

3. Main subsystems

In this section a description of the main DTT subsystems is proposed. The DTT design has been designed following the flexibility concept, that is the capability to incorporate the best candidate divertor concept even at a later stage of its realization, on the basis of the studies carried out in

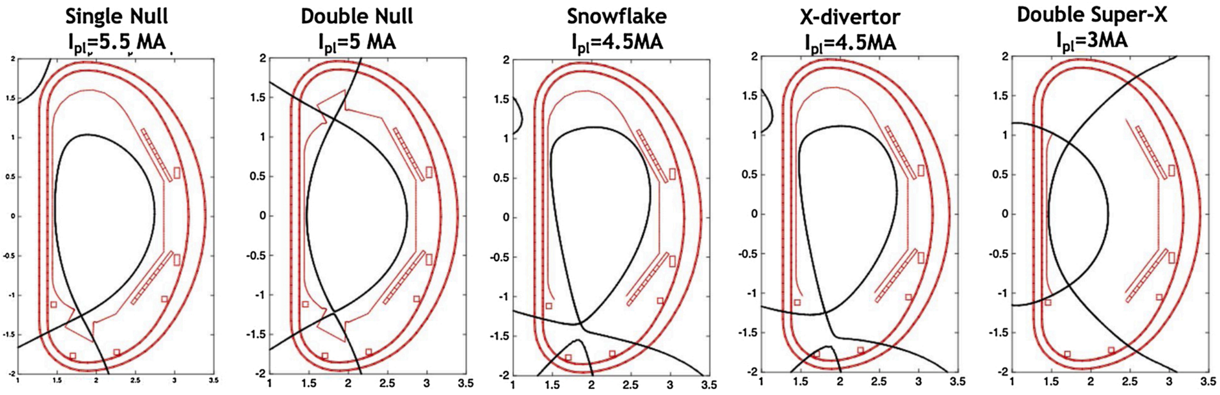

Fig. 2. DTT configurations.

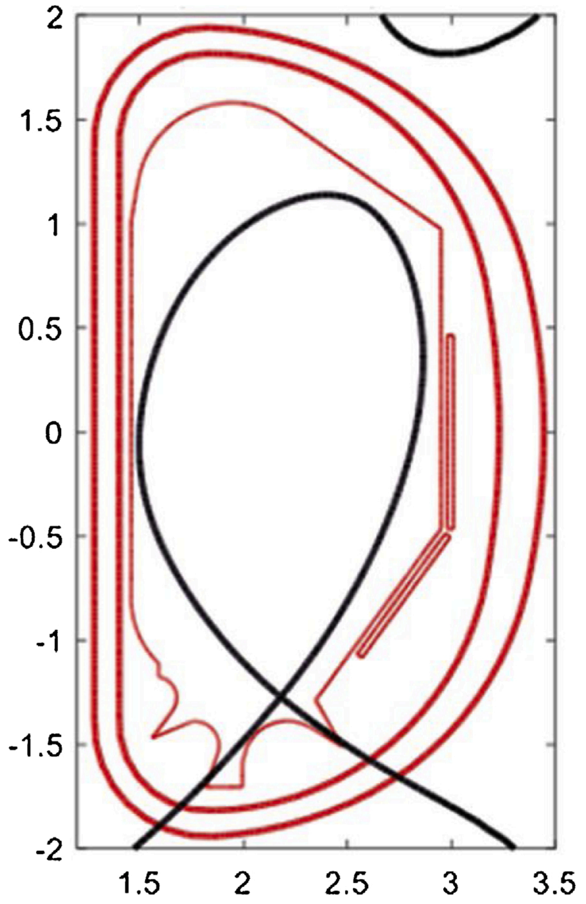

Fig. 3. Sigle null configuration with negative triangularity with $\delta_{95\%}^{upper} = -0.3$ and $\delta_{95\%}^{lower} = 0.05$.

present tokamaks involved in the PEX activities (around 2022–2023). In Fig. 2, the ACs considered in DTT are illustrated. The reference configuration is the Single Null with a flat-top plasma current of 5.5MA; however the machine is able to incorporate a Double Null at 5MA, a Snowflake and X-Divertor at 4.5MA and a Double Super-X at 3MA (even if, due to the reduced volume and plasma current, DSX is not considered in the last upgrade of the device).

More recently, the compatibility of the device with a negative triangularity configuration has been considered, as shown in Fig. 3.

Preliminary analysis has been performed in terms of optimization of the in-vessel components (FW, divertor…), compatibility with the CS/PF coils system, controllability of the configuration, transport and edge modelling.

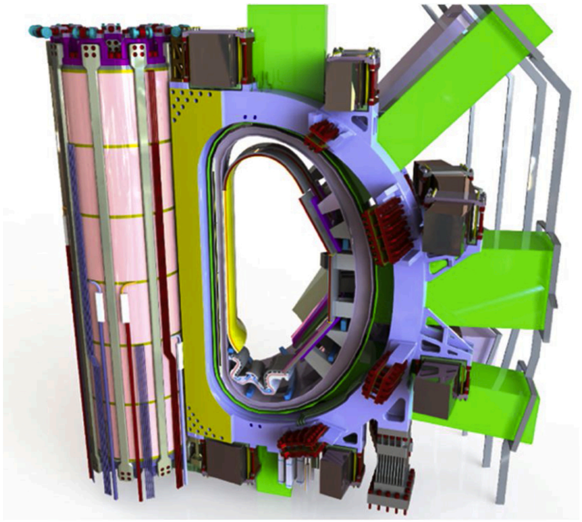

Fig. 4. DTT magnetic system.

Table 3
PF coils system.

COILS	MATERIAL	I_{max}	B_{peak}
PF1 & PF6	Nb3Sn	28.3kA	9.1T
PF2 & PF5	NbTi	27.1kA	4.2T
PF3 & PF4	NbTi	28.6kA	5.3T

3.1. *Magnetic system*

The DTT magnetic system [14–20], shown in Fig. 4, includes

- a toroidal system composed by 18 TF superconducting cable-in-conduit conductor (CICC) coils in Nb3Sn with $B_{peak} = 11.9T$ and $I_{max} = 42.5kA$ able to provide up to 6 T over the plasma major radius;
- a central solenoid (CS) divided in 6 independently fed modules; the CS is composed by Nb3Sn CICC coils with $B_{peak} = 13.6T$ and $I_{max} = 31.3kA$ able to provide a poloidal flux up to 16.6 Vs in the plasma breakdown; the design of the Central Solenoid has been changed respect to respect to [7–9] in order to increase the performance of the machine in terms of possible flux swing.
- a poloidal field (PF) coil system composed by 6 independent coils whose main parameters are reported in Table 3

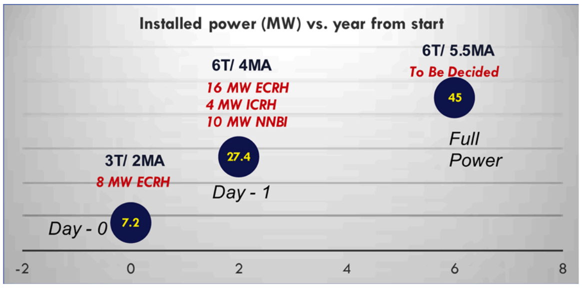

Fig. 5. Planning for the DTT heating system. The blue circles indicate the power injected to the plasma.

- 2 in-vessel up-down symmetric copper coils independently fed for the control of the vertical unstable mode and the implementation of a fast radial control of the plasma centroid;
- 4 divertor in-vessel copper coils for the local modifications of the magnetic configuration in the divertor region and the implementation of power exhaust feedback control strategies.

The superconducting and copper strands procurements, launched in spring 2019, has been assigned and the first strands have been delivered to the ENEA Research Centre in Frascati in 2020.

The conceptual design of TF coils, CS and PF coils has been concluded and in the beginning of 2021 the call for tenders for the TF will be launched. The conceptual design of the copper in-vessel coils will be concluded in the first half of 2021.

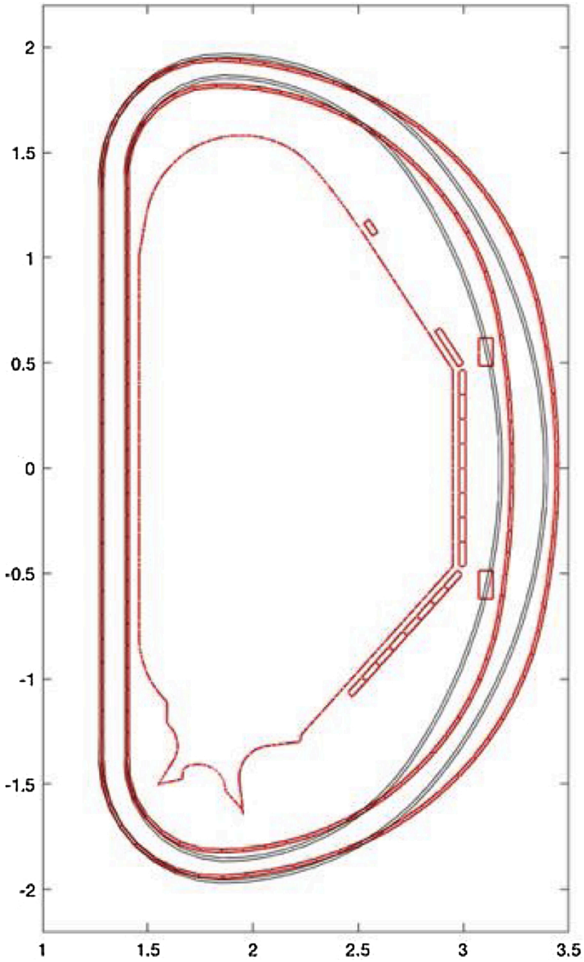

Fig. 6. Poloidal section of the new DTT vacuum vessel (red) compared with the old version (in black).

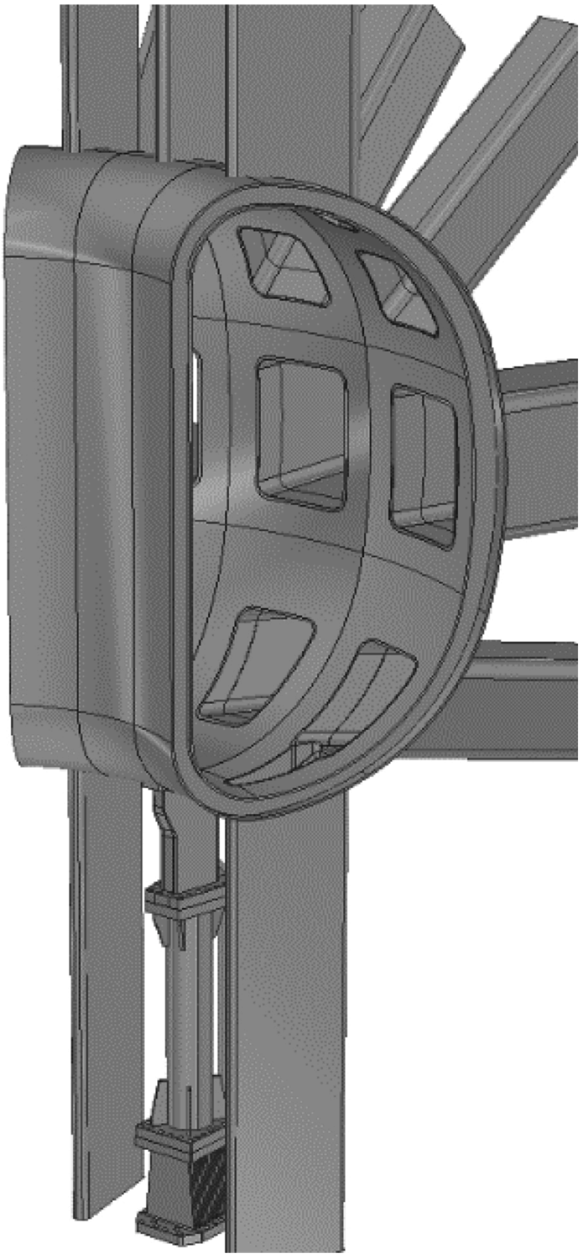

Fig. 7. DTT vacuum vessel.

3.2. Additional heating

A mix of different heating systems will provide a 45 MW power contribution in the final stage with the aim to reach $P_{sep}/R = 15$ MW/m. The DTT Baseline considers:

- ECRH: based on 4 clusters of 8 gyrotron at 170 GHz/1 MW (to resonate at 6 T), with an installed power up to 32 MW. The transmission losses are estimated in 10 %.
- ICRH: two modules composed by two antennas feed in parallel by a couple of tetrodes at 60–90 MHz with 1 MW/Tetrode, with an installed power up to 8 MW. The transmission losses are estimated in 25 %.
- NNBI: negative ion injector 500 keV/10 MW. No transmission losses are considered.

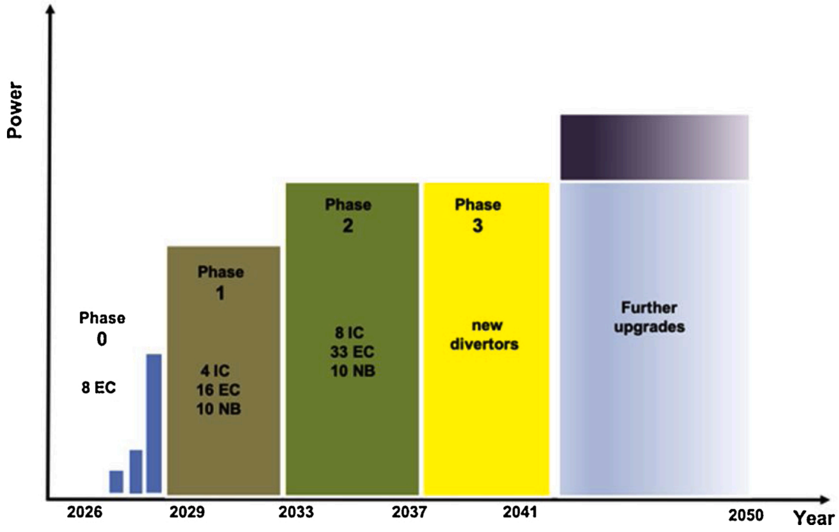

Fig. 8. DTT planning.

Three different phases are foreseen for the heating systems, as shown in Fig. 5. In the Day-0, the installation of one cluster of ECRH is planned with a total installed power of about 8 MW and a power injected to the plasma of 7.2 MW. At Day-1, after 2 years, two clusters of ECRH (about 16 MW), one module of ICRH (4 MW) and the NNBI (10 MW) will be installed, with a total installed power of 40 MW and a power injected to the plasma of 27.4 MW. Finally, after approximately 6 years, the full power of almost 45 MW injected to the plasma will be reached. The power distribution in the final stage is still open, but the more promising option considers 32 MW ECRH, 8 MW ICRH, 10 MW NBI.

Details on the DTT heating systems can be found in [21–25].

3.3. Vacuum vessel

The DTT vacuum vessel [27] includes

- the main vessel composed by two “D” shaped shells in stainless steel of 1.5 cm segmented in 18 modules joined by field welding;
- a water and boron shielding at 60–80 degrees;
- the system of ports for maintenance of the in-vessel components (divertor cassette, first wall) and allocation of diagnostic and heating equipment: 5 access ports for each module.

The design of the vacuum vessel has been significantly changed respect to [7–9], as shown in Fig. 6, to make it compatible with the new plasma major radius R = 2.19 m and able to accommodate the new set of plasma ACs. The maximum vacuum vessel variation in the outboard region is of the order of 10 cm.

Both a mechanical analysis under VDE and a thermal hydraulic analysis for the validation of the shielding solution has been computed. A 3D view of the DTT vacuum vessel is illustrated in Fig. 7.

Concerning the new design of the in-vessel components, in the first half of the 2021 the conceptual design of first wall, the stabilizing plates and in-vessel coils will be concluded.

3.4. Divertor

The main objective of the DTT project is to test several divertor design and configurations, from the standard single null to alternative configurations like X-Divertor, Snowflake and negative triangularity.

This need has inspired the whole project of the facility. In particular the design of VV, ports and RH devices takes into account application and testing of a Liquid Metal Divertor.

Therefore, one of the key characteristics pursued by the design is the flexibility in installing and testing different divertor modules; therefore

- VV and in-vessel components compatible with different divertor concepts;
- high modularity and easiness in replacing the divertor by remote handling in a relatively short time;
- VV ports designed to allow easy replacement of different divertors.

DTT will initiate operating with standard SN configuration but the testing with all the possible different magnetic divertor configurations, with the full available additional power, is planned.

EUROfusion will maintain the liaison with the DTT facility within the WPDIV work package, in order to design and qualify the optimum alternative divertor solution identified as feasible for DEMO, to be implemented and validated in DTT. Special attention will be given to fostering the synergies with the DEMO design.

3.5. Additional subsystems

Further details on the main components as well as on the additional systems can be found in [6] and in [10–28]. In particular, the relevant additional subsystems include the First Wall [6]; the Shield and Cryostat [6]; the Data Acquisition, Diagnostics and Control Systems [10–13]; the Remote Handling [28]; the Cooling and Shielding Systems [23]; the Pumping and Fuelling Components [6]; the Auxiliary Systems [6].

4. Scheduling

DTT should start its operation at the end of 2026. To be coherent with this plan, the realization of the device will cover a time of around 7 years, starting from the first tender (in 2019) up to full commissioning and the first plasma. The operations should then cover a period of at least 25 years, up to the initial phases of the DEMO realization. The DTT planning foresees five phases, as shown in Fig. 8. The first three phases, from *‘Phase* 0’ to *‘Phase* 2’, with a total duration of 11 years, are characterized by a gradual increase of the additional power from 8 MW up to 45 MW. (the total power is reached at the beginning of Phase 2, approximately 6 years after the first plasma). The *‘Phase* 3’ is dedicated to the testing of alternative divertors and the final phase can be used for further upgrades.

5. Status and perspectives

DTT is a European Facility, fully open to international cooperation, projected to face with one of most challenging issue in the fusion road map.

It has been conceived to tackle in a fairly integrated fashion the power handling issues in view of a reliable DEMO design by experimenting innovative plasma operating scenarios and new technologies.

As an additional strategic goal, DTT would like also to test effective schemes in managing and control complex construction and operation machine. In addition, it will support the development of a new generation of physicists, engineers, technologists duly trained by highly experienced persons on a up to date device.

Declaration of Competing Interest

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

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