CONFERENCE PRE-PRINT

THE DIVERTOR TOKAMAK TEST FACILITY RESEARCH PLAN

P. MARTIN
Consorzio RFX and University of Padova
Padova, Italy
Email: piero.martin@unipd.it

C. ANGIONI
Max-Planck-Institut für Plasmaphysik
Garching, Germany

S. BREZINSEK
Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung—Plasmaphysik
Jülich, Germany

F. CRISANTI
University of Tuscia
Viterbo Italy

C. DAY
Kyoto Fusioneering
Tokyo, Japan

G. DOSE
General Atomics
San Diego, CA, United States of America

M.V. FALESSI
ENEA and INFN
Frascati, Italy

G. GIRUZZI
CEA, IRFM
Saint Paul Lez Durance, France

P. INNOCENTE
ISTP-CNR
Padova, Italy

P. MANTICA
ISTP-CNR
Milano, Italy

E. NARDON
CEA, IRFM
Saint Paul Lez Durance, France

C. SOZZI
ISTP-CNR
Milano, Italy

D. TERRANOVA
Consorzio RFX and CNR ISTP
Padova, Italy

E. TSITRONE
CEA, IRFM
Saint Paul Lez Durance, France

D. VAN EESTER
Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung—Plasmaphysik
Jülich, Germany

P. VINCENZI
Consorzio RFX and CNR ISTP
Padova, Italy

G. VLAD
ENEA
Frascati, Italy

M. WISCHMEIER
Max-Planck-Institut für Plasmaphysik
Garching, Germany

THE CONTRIBUTORS TO THE DTT RESEARCH PLAN*

THE DTT CONTRIBUTORS†
DTT S.c.a r.l.,
Italy

Abstract

This paper summarises the content of the Divertor Tokamak Test facility (DTT) Research Plan. DTT, presently under construction in the Frascati (Italy) ENEA site, will be a device with breakeven class performance, which is designed to address one of the main challenges towards the construction of a fusion power plant, i.e., the development of credible solutions for the heat exhaust.

1. INTRODUCTION: THE DTT RESEARCH PLAN

The Divertor Tokamak Test facility (DTT) is presently under construction in the Frascati (Italy) ENEA site. The construction is managed by a public-private Consortium where the major stakeholders are ENEA (70%) and ENI (25%). DTT will be a device with breakeven class performance, and its main mission is to address one of the main challenges towards the construction of a fusion power plant, i.e., the development of credible solutions for the effective and reliable management of the power exhaust.

This paper is based on the DTT Research Plan [1], describes the objectives and research strategy of the DTT experiment [2,3,4], and proposes a set of programmatic headlines of its scientific programme. The activity for the preparation of the DTT Research Plan (DTT-RP) has been performed during the past three years by an international team comprising approximately 100 European fusion scientists belonging to 20 research institutes from 10 different countries. The DTT-RP is an extensive document (~200 pages) organized in nine chapters and nine technical appendices, which provide a synthetic description of the device main characteristics. The RP 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 will be one of the world most advanced tokamaks in the next decade. The main parameters of DTT are shown in Table 1.

---

* See Appendix 1

† For the list, see [3]

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 [4]. 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.

The DTT heating and current drive capability, at the end of its progressive implementation, will be provided by three different systems:

— ECRH: based on 4 clusters of 8 gyrotrons at 170 GHz/1 MW (to resonate at the fundamental electron cyclotron frequency for BT ~ 6 T or at the second harmonic for BT ~ 3 T), with an installed power up to 32 MW
— ICRH: two modules composed by two antennas fed in parallel by a couple of tetrodes at 60–90 MHz with 1 MW/Tetrode, with an installed power up to 9.5 MW.
— NNBI: one neutral beam injector based on the negative ion technology, at the energy of 510 keV and an installed power of 10 MW.

Figure 2 compares a number of dimensionless parameters of DTT with those of ITER (2019) and DEMO (2018) baseline scenarios. For DTT we show both the reference baseline scenario at 0.5 of the Greenwald density n_{GW} and one at lower density of 0.32 n_{GW}. We used the following definitions: $\upsilon_e * = 69.21\ (q\ R\ n_e\ Z_{eff}\ \ln \Lambda_e)/(T_e{}^2\ \epsilon^{3/2})$ [5] with $\ln \Lambda_e = 15.2 - \frac{1}{2}\ln n_e(E20\ m^{-3}) + \ln T_e(keV)$, $\epsilon = r/R$, with local values of r [m], q, Z_{eff}, n_e [E19 m^{-3}], T_e [eV]; $\rho * = 4.57\ 10^{-3}\sqrt{T_i\ m_i}\ /\ (a\ B_{tor})$ with T_i in keV, m_i=mass number (=2.5 for D-T), B_{tor} in T, a in m; $\beta=2\mu_0\, p\ /B_{tor}{}^2$ with p the pressure in Pascal; $\beta_N = \beta\ a\ B_{tor}/I_{pl}$ with I_{pl} in MA.

DTT has relevant dimensionless parameters as close as possible to those typical of ITER and DEMO-class reactors:

— the wall load parameter P_{SOL}/R ~ 15 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

TABLE 1: DTT MAIN DESIGN PARAMETERS

major radius *R* (m)	2.19
minor radius *a* (m)	0.70
Volume (m^3)	35
Plasma current (MA)	5.5
Vacuum $B_{toroidal}$ at *R*=2.19 m	5.85
Electron density $\overline{n_e}$ (10^{20} m^3)	1.5
Auxiliary power P_{tot} (MW)	45
P_{ECRH} (MW)	29
P_{ICRH} (MW)	6
P_{NBI} (MW)	10

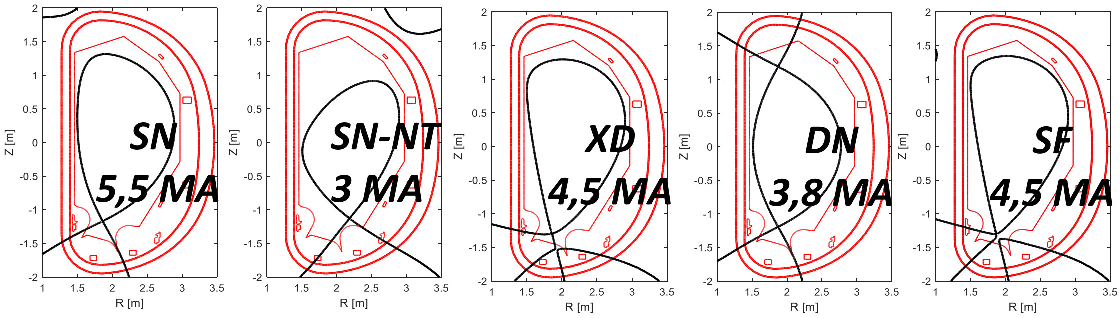

Figure 1

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.

The DTT Research Program is organized in nine chapters and nine technical appendixes, which provide a synthetic description of the device main characteristics; it follows the expected evolution of the machine along three distinct phases described in [3] 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 discussed in the following sections.

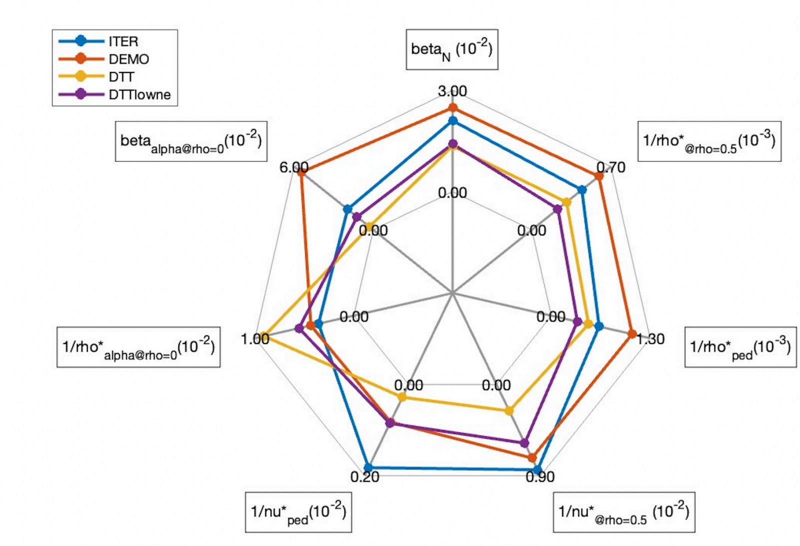

Figure 2

2. BASELINE AND ADVANCED SCENARIOS

The development and assessment of baseline and advanced scenarios for different divertor configurations has been realized, both at positive and negative triangularity, and at various currents and magnetic fields.

Figure 3 shows the equilibria used for positive triangularity: (a) upper triangularity δ_{up}=0.4 and lower triangularity δ_{low}=0.48 and for negative triangularity: (b) lower δ, δ_{up}=-0.35, δ_{low}=0.05; and (c) high δ, δ_{up}=-0.5, δ_{low}=0.05.

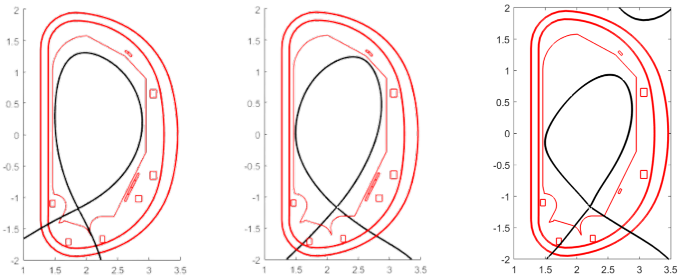

Figure 3 (a,b,c)

A very important feature of DTT is its flexibility in terms of divertor configurations. Note that change of divertor configuration may happen within the same discharge.

Figure 4 [taken from 6] shows the 1-d full power baseline scenarios profiles simulated with integrated modeling tools, such as JINTRAC or ASTRA, with the transport models TGLF or QuaLiKiz. The evolution of the whole plasma discharge, from the early ohmic limiter phase up to the H-mode flat-top phase, is simulated [7]. All the different phases (L-mode, L-H transition and H-mode) are treated in a single simulation, with the plasma parameters at the L-H transition determining the H-mode pedestals.

Given the choice of a Greenwald fraction of about 0.5 for the reference full power scenario, we find T_e>T_i over almost the whole plasma radius. It is conceivable to raise the Greenwald fraction, leading to a better balance between T_e and T_i , but this may happen mostly via reduction of T_e, because high ion stiffness tightly locks T_i profile to the ITG critical gradient. Although the electron density is moderately peaked in the full power scenario, the tungsten does not accumulate in the plasma center.

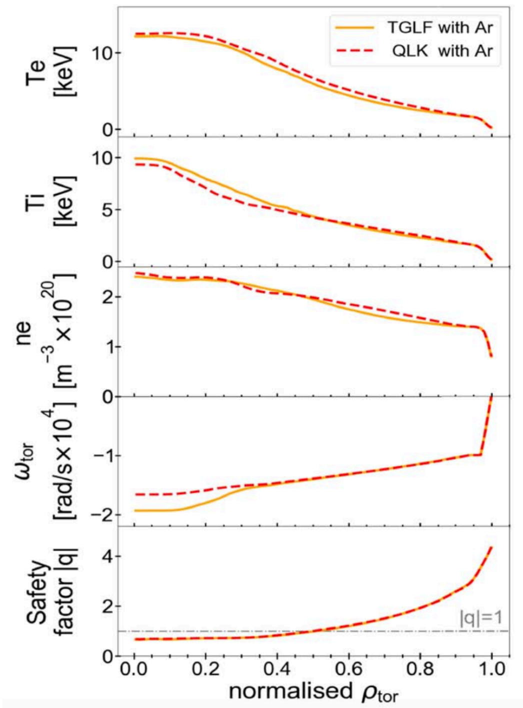

Figure 4

Since the baseline scenario is characterized by a large radius of the q=1 and large sawteeth, a Hybrid scenario has also been studied at I_p=3.8 MA, n_e=0.45 n_{GW}, characterized by early X-point formation and a fast (600 kA/s) ramp-up assisted by ECH and ECCD, achieving at flat-top a wide low shear region and q_0~1 marginally sustained for > 12 s [8].

Experiments in AUG and TCV, as well as gyrokinetic simulations and transport predictions, are ongoing to investigate whether a Negative Triangularity (NT) L-mode for DTT full-power scenario would perform similarly to the positive triangularity (PT) H-mode reference scenario avoiding ELMs [9]. In the TCV and AUG devices, dedicated experiments with DTT-like shapes have been realized. In TCV, experiments suggest that a large beneficial effect of NT comes from the plasma edge and SOL, even with the relatively small triangularity of the DTT NT scenario. This leads to the evidence that NT L-modes have better performance than PT L-modes with the same power input. Same central pressure is reached in NT L-mode as in PT H-modes with twice as much applied heating power. For AUG, the situation is less clear. NT plasmas are observed to make transition to H-mode more easily than for TCV, but they are characterized by smaller pedestals compared with PT plasmas with the same input power. Weaker or even no ELM activity is recorded. However, NT has a smaller beneficial effect for AUG than for TCV. In AUG NT plasmas are better than PT plasmas with the same input power only for the case with relatively low input power coming only from ECRH. With higher ECRH power or with mixed NBI and ECRH power, PT performs better than NT in AUG. Overall, Mariani et al. [9] conclude that the NT option is a viable alternative for the DTT full power scenario and provides high performance plasmas with reduced or absent ELMs. Work is ongoing to understand the origin of the different behavior of TCV and AUG and the possibility of extrapolating the results to DTT [10,11] .

3. TRANSPORT, MHD, AND 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 considering 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 NNBI and ICRH. 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 [12] 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.

DTT will be equipped with powerful tools to feedback control MHD stability.

Within the DTT vacuum vessel a system of 27 non-axisymmetric coils will be installed, each independently powered and arranged as in ITER in three toroidal rows with 9 coils each. A sketch of the system is shown in Figure 5. They will be used for

- Correction of error fields
- Mitigation or suppression of Edge Localized Modes (ELM-see dedicated section)
- Control of Runaway Electrons, synergistic with the Disruption Mitigation System (enhancing losses-see dedicated section)

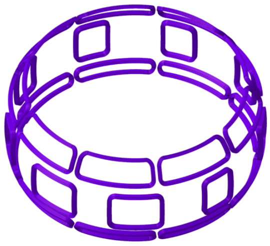

Figure 5

The powerful and flexible 32 MW ECRH system will be used also to control MHD stability, with the front-steering mirrors capable to direct the beams individually in real-time in the appropriate location. Numerical simulations done with a NTM module integrated in both JETTO-JINTRAC and in ETS have been performed to analyze NTM stability and its control in DTT. It is worth noting that given the β_N values at full power in DTT, the NTM issue may be less severe than in other devices

The free evolution of the 2/1 and 3/2 modes has been computed. Linear stability analysis showed a linearly stable equilibrium (Δ'_0=-3.6). Considering a linearly unstable tearing mode the saturation width is reached in ~3 s, as shown in Figure 6. Clearly the 2/1 mode needs to be controlled to avoid disruptions.

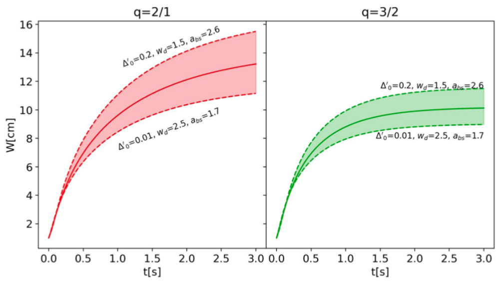

Figure 6

A complete study of ECRH stabilization has been done and has shown that NTM stabilization is possible in DTT, even for the most dangerous 2/1 mode [13]. Figure 7 shows the stabilizing effect using 5 MW of ECRH, as a function of the beam deposition width. As the beam width increases, the stabilizing effect is reduced.

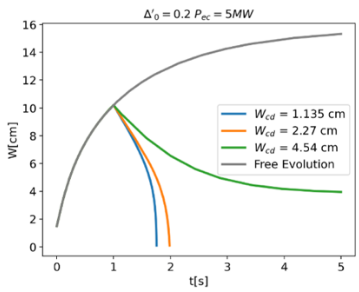

Figure 7

4. 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 both in terms of Z_{eff} and impurity concentration C_{imp}. The Single Null (SN) scenario allows detachment at full current with Z_{eff}=2.8 and an impurity concentration C_{imp}=1%. DTT will be equipped with a divertor gas injection system, which is traditionally used in tokamaks. Good pumping capacity in SN for both D and seeding gases is observed, while low seeding pumping is recorded for other divertor configurations

Figure 8 shows the simulated impurity concentration for various divertor configurations.

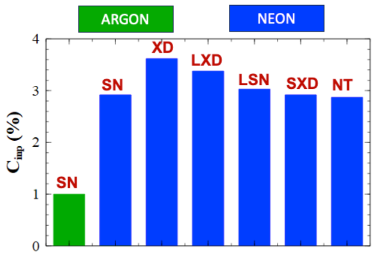

Figure 8

Figure 9 shows the electron temperatures and the power on the divertor at the inner and outer plates. When detached is achieved, the total power to the targets is < 6 MW/m^2, which is well below the maximum allowed for tungsten monoblocks (20 MW/m^2). Detachment is difficult at the Inner Vertical Target for X Divertor LX Divertor and at Outer Horizontal Target for NT.

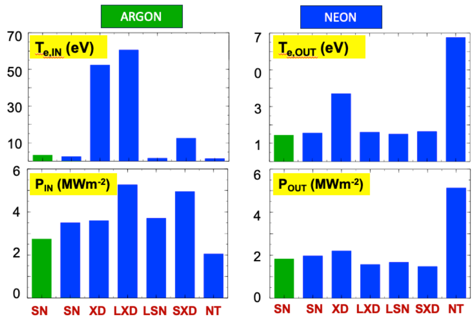

Figure 9

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 ~2% [14,15].

DTT will also 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.

5. DEVELOPMENT OF SMALL/NO ELMS SCENARIOS AND THEIR CONTROL, AND CONTROL OF OFF-NORMAL EVENTS

DTT will give the possibility of exploring the domain of existence and the performance of high toroidal field, high current stationary regimes that feature sufficiently small or no ELMs. In fact, DTT scenarios match the collisionalities at both the separatrix and the pedestal top that are expected in a future reactor, a critical element towards a complete and reliable core-edge integration.

DTT will be equipped with advanced systems to mitigate transient and off-normal events such as ELMs and disruptions respectively, with features like analogous systems present in ITER. The non-axisymmetric internal coils, previously discussed, will produce slowly rotating perturbations with toroidal mode number up to $n = 4$ and can be applied for the purpose of ELM control.

The reference full power scenario of DTT has a normalized pedestal collisionality (at $\rho_{pol} = 0.97$) of about $\nu* = 0.23$ and hence $\Delta W_{ELM}/W_{ped} \approx 9.6$ %. Given $W_{ped} = 3.56$ MJ, $\Delta W_{ELM} = 0.34$ MJ. Enhanced D-alpha (EDA) H-mode, quasi-continuous exhaust (QCE), X-Point radiatior, I-mode, Quiescent H-mode, Wide Pedestal Quiescent H-mode scenarios are possible candidates for ELM free regimes in DTT.

DTT will be equipped with a shattered pellet injection (SPI) disruption mitigation system like that in ITER. All the key DTT mechanical structures (first wall, vacuum vessel, magnet support, ...) have been designed to sustain up to around 1000 disruption at full power. Therefore, DTT is very well equipped to perform dedicated experimental campaigns to optimize the disruption control in ITER, a fundamental topic for its nuclear operation, as well as for the safe operation of any future tokamak.

3D simulations of disruption dynamics are being performed with the JOREK code. Simulation show that in the full power scenario SPI can efficiently radiate most of the plasma thermal energy in a few ms [16]. As far as runaway electron (RE) beam generation during DTT disruptions is considered, Day-0 scenario can be considered safe, removing the immediate need for RE beam current mitigation [17]. Nonetheless the RE avalanche may be large in the full performance scenario due to the large I_p, making DTT an interesting machine to study RE avoidance and mitigation techniques in view of ITER. RE current is observed to have effects on the nonlinear MHD dynamics [18]. The MHD activity is expected to increase, with potential benign effect on RE mitigation.

6. WALL CONDITIONING

Wall conditioning is key for plasma performance in high Z metallic devices (most high Z machines such as ASDEX Upgrade, ALCATOR C Mod, EAST or WEST perform regular low Z conditioning, using boronization or lithium coatings). Wall conditioning is of particular importance for starting a device after a vent or during an experimental campaign to perform specific high-performance programmes. Boronization is presently contemplated for ITER. Wall conditioning for DEMO is still an open issue, given the extremely high duty cycle foreseen. DTT is equipped with a variety of wall conditioning techniques of relevance for ITER: baking, glow discharge cleaning (GDC), standard boronization, Ion Cyclotron Wall Conditioning (ICWC). It should be noted that only ICWC can be performed between plasma discharges, while GDC/boronization can be performed over a weekend with the toroidal field off, as is the case for all superconducting devices.

DTT will address the following points concerning wall conditioning:

- Optimizing the wall conditioning sequence after an anomalous event (baking / GDC / boronization);
- Monitoring the impact of GDC/boronization on plasma recycling (main fuel) and intrinsic impurities (tungsten and oxygen level in particular) during a campaign and defining the optimized boronization parameters / frequency. In particular, assessing the oxygen source and how it evolves following boronizations would bring valuable input for ITER/DEMO;
- Investigating the boron deposited layers (structure, thickness, uniformity, stability, fuel trapping ...) as a function of the boronization parameters.

Wall erosion, W migration, D retention and removal studies will be performed 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.

7. CONCLUSIONS

The DTT project is in its construction phase, with a large fraction of the budget already committed in industrial contracts. The design and construction activities are accompanied by intensive physics studies, carried out by various Italian institutes with international collaborations, including theory, modelling, diagnostic equipment definition and design and control schemes developments. These studies are not limited to the DTT main mission of heat exhaust, but involve topics such as transport, MHD, heating and current drive, energetic particle physics, because the solution to the heat exhaust challenge requires an approach that ensures core-edge integration.

In 2022, it was decided to build on these studies to produce the DTT Research Plan, involving the broadest possible community of European fusion institutes. The result of this activity is the first version of the DTT-RP. Some elements of it have been presented in this contribution. The complete document describes the objectives and research strategy of the DTT experiment, culminating in a set of programmatic headlines. It should be stressed that the DTT-RP is a living document, which will be regularly updated during the construction phase, and which will constitute the basis for the construction of the DTT scientific programme and of subsequent device upgrades.

8. APPENDIX 1: CONTRIBUTORS TO THE DTT RESEARCH PLAN

CEA, IRFM, France: J.F. Artaud, H. Bufferand, G. Ciraolo,Y. Corre, R. Dumont, G. Falchetto, M. Firdaouss, A. Gallo, J. Garcia, G. Giruzzi, J. Hillairet, E. Joffrin, X. Litaudon, P. Maget, M. Missirlian, J. Morales, E. Nardon, M. Richou, R. Sabot, E. Tsitrone

CNR-ISTP, Milano, Italy: E. Alessi, B. Baiocchi, N. Bonanomi, I. Casiraghi, A. Dal Molin, L. Figini, F. Ghezzi, P. Mantica, A. Mariani, S. Nowak, D. Ricci, G. Rubino, C. Sozzi, E. Vassallo.

Consorzio CREATE, Napoli, Italy: R. Albanese, R. Ambrosino.

Consorzio RFX, Padova, Italy: F. Auriemma, P. Agostinetti, T. Bolzonella, D. Bonfiglio, M. Dalla Palma, C. De Piccoli, M. Gobbin, P. Innocente, P. Martin, A. Murari, S. Peruzzo, L. Pigatto, L. Piron, G. Spizzo, D. Terranova, F. Veronese, N. Vianello, P. Vincenzi, M. Zuin.

DIFFER, The Netherlands: S. Wiesen

ENEA, Frascati, Italy: L. Boncagni, A. Cardinali, N. Carlevaro, A. Castaldo, C. Castaldo, S. Ceccuzzi, M. Ciotti, M.V. Falessi, D. Fiorucci M. Iafrati, C. Piron, G. Ramogida, G. Vlad, F. Zonca.

EPFL, Switzerland: C. Theiler, D. Testa.

Forshung Zentrum Julich, Germany: S. Brezinsek J.W. Coenen, D. Van Ester, M. Wirtz.

General Atomics, San Diego, CA, USA: G. Dose.

KIT, Germany: T. Giegerich, S. Varoutis.

KTH, Sweden: L. Frassinetti

Kyoto Fusion Engineering, Kyoto, Japan: C. Day.

ITER Organisation, Cadarache, France: G. Brochard

Max-Planck IPP, Garching, Germany: C. Angioni, C. Hopf, P. Lauber, R. Neu, M. Wischmeier.

NCSRD, Greece: Y. Kominis, C. Tsironis

Politecnico di Torino, Italy: R. Bonifetto, G. Nallo, F. Porcelli, F. Subba.

Technical University of Denmark: M. Salewski

UKAEA, CCFE, Culham UK: P. Jacquet, D. King.

Università della Tuscia, Viterbo, Italy: L. Balbinot, F. Crisanti

Università di Milano Bicocca, Milano, Italy: L. Aucone, M. Cavedon, M. Nocente.

University of Aix-Marseille, CNRS, France: J. Gaspar

ACKNOWLEDGEMENTS

The authors acknowledge the precious contributions of the DTT team.

REFERENCES

1 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
2 F. ROMANELLI et al., Nucl. Fusion **64** (2024) 112015.
3 F. ROMANELLI et al, "The Divertor Tokamak Test project: towards the initial operation", this conference
4 G.M. POLLI et al, this conference
5 SAUTER O. et al 1999 Phys. Plasmas **6** 2834
6 CASIRAGHI I. et al 2023 Plasma Phys. Control. Fusion **65** 035017
7 BONANOMI N. et al., Nucl. Fusion 65 (2025) 016005
8 AURIEMMA F. et al., EU-US TTF 2025
9 MARIANI A. et al., Nucl. Fusion **64** (2024) 106024
10 MANTICA P. et al., EU-US TTF 2025
11 MARIANI A. et al., EFTC 2025
12 VARIOUS AUTHORS Special Section of Fusion Engineering and Design Vol. 122, 2017, 253-294
13 L. BONALUMI, FISMAT Conference (2025)
14 BALBINOT L. et al, Nuclear Materials and Energy 27 (2021) 100952
15 BALBINOT L. et al., Nuclear Materials and Energy 42 (2025) 101835
16 KRYZHANOVKYY ET AL (courtesy of)
17 EMANUELLI et al, submitted to Fusion Engineering and Design
18 SINGH ET AL (courtesy of)