DTT proposal: Engineering aspects

R. Albanese, on behalf of the WPDTT2 team* & the DTT project proposal contributors*

Summary

• Introduction

• Physical & Technological Requirements

• Choice of main machine parameters

• Main features

• Improvements presented to panels & in FED SI: DTT

• Possible improvements under investigation

• Boundary conditions for Phase II
Introduction
Introduction

- Activity started under EUROfusion WPDTT2 after definition of technical requirements and choice of main machine parameters
- Proposal presented in the “blue book” prepared in less than three months to match a deadline related to Juncker’s funds (July 2015)
- Some improvements proposed at a later stages (presented to the International PEX Panel in July 2016, to the PMU in February 2017 and in the Special Issue of FED (2017), e.g.:  
  - FW temperature 300-400 °C
  - Experimental tests at SPC Labs showed 30% superior performance compared to ITER superconductors*:  
    - [https://www.euro-fusion.org/newsletter/superconducting-cables-for-demo/](https://www.euro-fusion.org/newsletter/superconducting-cables-for-demo/)
  - extensive studies on SOL simulations and plasma performance
  - use of internal coils, 3 MA long leg, 5.5 MA SFD, ...

* [https://www.euro-fusion.org/newsletter/superconducting-cables-for-demo/](https://www.euro-fusion.org/newsletter/superconducting-cables-for-demo/)
Introduction

Fusion Engineering and Design Special Issue: DTT

https://www.create.unina.it/dtt2/index.php/WPDTT2_Task5/FED_SI_DTT
Introduction

• Possible improvements are under investigations, e.g.:
  • Sensitivity studies with respect to the dimension
  • Current drive
  • Other divertors (for DN, SF, long leg, LM divertor concepts)
  • Implications of the selection of a different site

• Other possible improvements are planned during Phase II based on
  internal reviews as well as comments, suggestions, proposals coming
  from EUROfusion and the international fusion community
  with clear boundary conditions on:
  • Time (≈ 6 months)
  • Resources (should not increase)
  • Objectives (test PEX solutions applicable to DEMO)
  • Flexibility (not reduced and possibly improved)
  • Framework (with EUROfusion endorsement and contribution)
  • Team (possibly enlarged with EU and Int’l colleagues)
  • Management (clear roles defined during Phase II)
Physical & Technological Requirements
Physical & Technological Requirements

Physical requirements
- Preservation of 4 DEMO relevant parameters: $T_e$, $v^* = L_d/\lambda_{ei}$, $\Delta_d/\lambda_0$, $\beta$
- Relaxation on normalized Larmor radius: $(\rho_i/\Delta_d)^* R^* \text{ value similar to DEMO}$
- Integrated scenarios: solutions compatible with plasma performance of DEMO

Technological requirements
- $P_{sep}/R \geq 15 \text{ MW/m}$
- Flexibility in the divertor region so as to possibly test several divertors
- Possibility to test alternative magnetic configurations
- Possibility to test liquid metals
- Integrated scenarios: solutions compatible with technological constraints of DEMO
- Budget constraint: within 500 M€


Choice of main machine parameters
### Choice of main machine parameters

**MAIN DTT PARAMETERS FOR THE REFERENCE SINGLE NULL SCENARIO**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>R (m)</td>
<td>2.15</td>
</tr>
<tr>
<td>a (m)</td>
<td>0.7</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>6</td>
</tr>
<tr>
<td>B_T (T)</td>
<td>6</td>
</tr>
<tr>
<td>V (m³)</td>
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<tr>
<td>P_ADD (MW)</td>
<td>45</td>
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<tr>
<td>H98</td>
<td>1</td>
</tr>
<tr>
<td>⟨n_e⟩ (10²⁰ m⁻³)</td>
<td>1.7</td>
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<tr>
<td>n_e/n_eG</td>
<td>0.45</td>
</tr>
<tr>
<td>⟨T_e⟩ (KeV)</td>
<td>6.2</td>
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<tr>
<td>τ (sec)</td>
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<tr>
<td>n_e(0) (10²⁰ m⁻³)</td>
<td>2.2</td>
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<tr>
<td>T_e(0) (KeV)</td>
<td>10.2</td>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>β_N</td>
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</tr>
<tr>
<td>τ_Res (sec)</td>
<td>8</td>
</tr>
<tr>
<td>V_{Loop} (V)</td>
<td>0.17</td>
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<tr>
<td>Z_{eff}</td>
<td>1.7</td>
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<td>P_{Rad} (MW)</td>
<td>13</td>
</tr>
<tr>
<td>P_{Sep} (MW)</td>
<td>32</td>
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<tr>
<td>T_{Ped} (KeV)</td>
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<tr>
<td>n_{Ped} (10²⁰ m⁻³)</td>
<td>1.4</td>
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<tr>
<td>β_p</td>
<td>0.5</td>
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<tr>
<td>P_{Div} (MW/m²) (No Rad)</td>
<td>~ 55</td>
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<tr>
<td>P_{Sep}/R (MW/m)</td>
<td>15</td>
</tr>
<tr>
<td>P_{Tot B/R} (MW T/m)</td>
<td>125</td>
</tr>
<tr>
<td>λ_q (mm)</td>
<td>~ 2</td>
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**Comparison with ITER and DEMO**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DTT</th>
<th>ITER</th>
<th>DEMO</th>
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<tbody>
<tr>
<td>R (m)</td>
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<td>6.2</td>
<td>8.77</td>
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<td>a (m)</td>
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<td>B_T (T)</td>
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<td>5.3</td>
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<td>V (m³)</td>
<td>33</td>
<td>853</td>
<td>2218</td>
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<td>P_ADD</td>
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<td>450</td>
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<td>H98</td>
<td>1</td>
<td>1.72</td>
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<tr>
<td>⟨n_e⟩ /n_eG</td>
<td>0.45</td>
<td>0.85</td>
<td>1.1</td>
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<tr>
<td>⟨T_e⟩ (KeV)</td>
<td>6.2</td>
<td>8.5</td>
<td>12.6</td>
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<tr>
<td>τ_E (s) (H_{98}=1)</td>
<td>1.5</td>
<td>1.6</td>
<td>2.1</td>
</tr>
<tr>
<td>β_N</td>
<td>2.4</td>
<td>2.3</td>
<td>1.3</td>
</tr>
<tr>
<td>ν^* (10⁻³)</td>
<td>3.7</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td>T_{Ped} (KeV)</td>
<td>3.1</td>
<td>4.3</td>
<td>7.0</td>
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<tr>
<td>n_{Ped} (10²⁰ m⁻³)</td>
<td>1.4</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>ν_{Ped} (10⁻²)</td>
<td>6.3</td>
<td>6.2</td>
<td>2.8</td>
</tr>
<tr>
<td>ELM energy (MJ)</td>
<td>1.2</td>
<td>24</td>
<td>140</td>
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<tr>
<td>P_{Sep}/R (MW/m)</td>
<td>15</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>P_{Tot B/R} (MW T/m)</td>
<td>1.7</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>P_{Div} (MW/m²) (70% Rad.)</td>
<td>27</td>
<td>27</td>
<td>42</td>
</tr>
<tr>
<td>Pulse length (s)</td>
<td>125</td>
<td>100</td>
<td>290</td>
</tr>
<tr>
<td>λ_{int} (mm)</td>
<td>100</td>
<td>400</td>
<td>7000</td>
</tr>
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</table>
Main features
Main features

• DTT has most of the features of a next generation tokamaks but:
  • no tritium ⇒ no fusion reactions, no blanket, no double-walled VV (even if the expected neutron flux is significant, namely $\approx 9 \cdot 10^{11} \text{ n cm}^{-2} \text{ s}^{-1}$)
  • no significant current drive contribution in the original proposal

http://fsn-fusphy.frascati.enea.it/DTT

July 2015

and

Fusion Engineering and Design, Special Issue: DTT
https://www.create.unina.it/dtt2/index.php/WPDTT2_Task5/FED_SI_DTT
Main features

- **Flexibility**

All coils separately fed (6 in the CS, 6 PF coils). In this way DTT can get the same configurations as DEMO with a single PF system of SC coils.

EU DEMO (DTT1/PMI)

DTT
Main features

- **Flexibility**

Further flexibility guaranteed by a number of in-vessel coils for vertical stabilization and local modifications of the magnetic configuration in the divertor region.

![Graphs showing magnetic field configurations](image)

**Relaxed SF-plus**

**XD**
Main features

- **Flexibility**

DTT offers an important opportunity for integrated control (e.g., plasma shape, position and power exhaust): many ports can be used for diagnostics, the diagnostics and control system can be designed from scratch and effectively integrated.

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**Strategy 2: Design Integration**

Diagnostic & Control system, Divertor topology and detailed components must be designed in an integrated way to ensure measurability of critical parameters and crucial systems maintenance.

Measurability of critical parameters is one of the divertor specs.
Main features

- **Flexibility**

*DTT offers the possibility to test different divertor concepts including both conventional and advanced solutions:*

**Divertor modules***

1) DTT W reference
2) Vapor Box
3) Golubchikov et al. JNM 1996

Evaporation
Condensation

We are doing preliminary calculation for #2
We have enough data to start project for a liquid Tin #1

**FW modification for DN operation***

To share power load between the UN and LN wobbling with the plasma up 1.0 - 1.5 s (i.e. 2-3 \( \tau_B \)) is foreseen. Modification of the upper left zone of the FW will be necessary.
A divertor configuration based on flat tile with CuCrZr heat sink, soft copper inter-layer and W armour is presently studied.
Water and CO\(_2\) presently considered.
Improvements presented to panels & in FED SI: DTT

- Some improvements have been obtained at later stages (presented to the Int’l PEX Panel in July 2016, to the PMU in February 2017 and in the Special Issue of FED (2017)

- FW temperature
  In the “blue book” the first wall (FW) temperature was 100° Celsius. Now the FW wall temperature is planned to be 300° Celsius, controlled by a flux of water or CO₂. In this way we avoid problems related to LM condensation and have conditions closer to the PFCs of a reactor (see https://doi.org/10.1016/j.fusengdes.2016.12.030 ). This also addresses the subject of PEX Ad-Hoc Group question #3 on flexibility.

- SC strands
  The DTT magnets shown in the “blue book” were based on ITER-like strands with slightly optimized performances, only 20% higher, which are now achievable. Experimental tests at SPC Labs have shown a 30% superior performance compared to ITER superconductors: https://www.euro-fusion.org/newsletter/superconducting-cables-for-demo/
Improvements presented to panels & in FED SI: DTT

- Alternative configurations (see Ambrosino’s talk)
  - DTT, as it is, can achieve a SX configuration with \( \frac{R_{\text{target}}}{R_{\text{xpoint}}} > 1.6 \) with \( I_p = 3 \text{MA} \) & \( q = 3.5 \) (see Annex II and comment AP2 in Annex I)
  - A SF configuration has been optimized so as to achieve 5.5 MA instead of 4 MA
  - The in-vessel coils have been used to get and control XD, SF+ & SF- configurations

Outer long leg configuration designed assuming
- Plasma current \( I_p = 3 \text{MA} \)
- \( \frac{R_{\text{target}}}{R_{\text{xpoint}}} \approx 1.6 \rightarrow \frac{B_{\text{target}}}{B_{\text{xpoint}}} \approx 1.6 \) (similar to DEMO)
- Plasma volume of \( V_{\text{SX}} \approx 20 \text{m}^3 \) (\( V_{\text{SN}} \approx 39 \text{m}^3 \))

Estimation of currents needed in a pair of in-vessel coils for S-X flux flaring (\( I = B_{\text{pol}} \cdot d_{\text{coils}} \cdot \frac{2\pi}{\mu_0} \)):
- DEMO with in-vessel coils distance of \( d_{\text{coils}} \approx 100 \text{cm} \) ⇒ \( I \approx 2.5 \text{MA} \)
- DTT with in-vessel coils distance of \( d_{\text{coils}} \approx 20 \text{cm} \) ⇒ \( I \approx 500 \text{kA} \)
- See other talks for further details on the remaining aspects (SOL, diagnostics, heating ...)
Possible improvements under investigation
Possible improvements under investigation

- **Sensitivity analysis on machine dimensions**

- A reduced size DTT with a major radius of 1.95 m (10% less than the original proposal) can accommodate a 5.5 MA plasma with $B = 6.15$ T.

- Within a fixed budget, more resources might be dedicated to spares, contingencies, and Padd increase at an earlier stage. Further performance optimization might also be achieved.

- CS dimension is reduced, with consequent reduction of the available flux and impact on flat top duration. Heating and current drive by EC waves is an important tool in order to minimise the flux consumption and maximise the discharge duration of the DTT machine.

- Reduction of the heating power (from 45 to 40 MW) has little impact on pulse duration ($\approx 90$ s)

- Larger effect (from 90 to 60 s) is predicted with Padd=20 MW (initial phase). However, this loss can be recovered operating at lower but still acceptable density ($\bar{n}_e = 1.3 \times 10^{20}$ m$^{-3}$).
Possible improvements under investigation

- **Ripple**
  - The TF ripple can be modified so as to static 3D field perturbations on purpose in the divertor region (e.g. by ferromagnetic inserts or varying separately even/odd TF coil currents).
  - Ferritic blocks can be inserted in the lower-outboard port used for maintenance. With a cross section of 0.7 m², a toroidal filling factor of 50% and a saturation field of 0.8 T we may get about ±3 mT corresponding to a ripple of 0.5% in the divertor region.

This also addresses the subject of PEX Ad-Hoc Group question #11 on flexibility.
Possible improvements under investigation

- **DN wobbling** (see also Di Gironimo's talk)

- *In a DN there is always a “principal” null affecting the topologic and physics properties, especially in DEMO or DTT where the SOL width is small.*

- *In the ongoing DEMO DN studies the up-down power sharing is realized by a wobbling technique*

- *In DTT, assuming the oscillation of zp within 5 mm, the drsep oscillation would be within 1.5 mm.*

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**Active Wobbling on DEMO: preliminary closed loop**

- The previous results have been used to implement a preliminary closed loop nonlinear simulation imposing a bang-bang controller on the imbalance circuit with:
  - \( v = 2 v_{\text{min}} = 34V \)
  - A switching condition given by the 0.1 ms\(^{-1}\) threshold of the plasma centroid vertical velocity

- The oscillations of the plasma vertical position have a period of about 0.5s, as predicted by the linearized model

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Active wobbling in DEMO. It is shown that the drsep oscillation (±7 mm) is about 1/3 of the vertical oscillation of zp (±19 mm).

**R. Wenninger et al., EUROFUSION WPPMI-CP(16) 15203**
Possible improvements under investigation

- **The DTT DN is not up-down symmetric.** For this reason the wobbling based on combined vertical stabilization, shape and power exhaust diagnostics & control will share the power about 25% up - 75% down, e.g. 1.5 s up, 4.5 s down

- **Another important point is the fatigue.** In this respect, in DEMO at least a frequency of 4 Hz has to be achieved:

  "The thermal fatigue analysis on the pipe interlayer has confirmed a reasonable lifetime for the divertor by using the sweeping as an emergency tool, i.e. to quickly react to a possible increase of heat flux above the nominal values, or as a steady state tool, if the frequency is raised to 4 Hz. No show stoppers have been found so far for the strike point sweeping technique in a DEMO environment."

  (see F. Maviglia et al., http://dx.doi.org/10.1016/j.fusengdes.2016.01.023 )

This also addresses the subject of PEX Ad-Hoc Group question #7 on flexibility.

- **Again, see other talks for further details on the remaining aspects**
Boundary conditions for Phase II
Boundary conditions for Phase II

- Other possible improvements are planned during Phase II based on internal reviews as well as comments, suggestions, proposals coming from EUROfusion and the international fusion community (including those arising in this WS) and trying to coordinate the objectives, the activities and the operations of DTT with the complementary experiments ongoing and planned in EUROfusion and Int’l machines in the area of Power Exhaust.

- A number of boundary conditions should be taken into account:
  - Time ($\approx 6$ months)
  - Resources (should not increase)
  - Objectives (test PEX solutions applicable to DEMO)
  - Flexibility (not reduced and possibly improved)
  - Framework (with EUROfusion endorsement and contribution)
  - Team (possibly enlarged with EU and Int’l colleagues)
  - Management (clear roles defined during Phase II)