“The conceptual design of the DTT superconducting magnet system”

Aldo Di Zenobio

on behalf of the DTT Magnet System design team:
R. Bonifetto, L. Savoldi, A. Zappatore and R. Zanino – Politecnico di Torino (NEMO Group)

and DTT design contributors:
Background & Project Objectives
4. How to face the challenges –
the missions for the realisation of fusion

Mission 1 – Plasma regimes of operation
Mission 2 – Heat-exhaust systems
Mission 3 – Neutron tolerant materials
Mission 4 – Tritium self-sufficiency
Mission 5 – Implementation of the integrated safety features of fusion
Mission 6 – Integrated DEMO design and system development
Mission 7 – Competitive cost of electricity
Mission 8 – Stellarator

M2. Heat-exhaust systems:
Demonstrate an integrated approach that can handle the large power leaving ITER and DEMO plasmas.
General objective: create a research infrastructure addressed to the solution of the power exhaust issues in view of DEMO.

Test Divertor alternative solutions & improve experimental knowledge in the PEX scientific area

- Replace Divertor by Remote Handling
- High Magnetic System flexibility to Implement Various Plasma configurations
Max. plasma current: **5.5 MA**

Inductive operation with a max high $\beta$ flat top up to **50 s**

Heating system providing **45 MW** (target)

(20-30 MW ECRH, 3-9 MW ICRH, 7-15 MW NNBI)

### DTT main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(m)/a(m)$</td>
<td>2.14/0.65 (SN/DN)</td>
</tr>
<tr>
<td>$A$</td>
<td>3.3 (SN/DN)</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>5.5</td>
</tr>
<tr>
<td>$B_T$ (T)</td>
<td>6.0 @ $R_0$</td>
</tr>
<tr>
<td>Neutron production rate (n/s)</td>
<td>1.2-1.5 $10^{17}$ DD + 1% DT</td>
</tr>
<tr>
<td>Maximum dwell time (s)</td>
<td>3’600</td>
</tr>
<tr>
<td>Nominal repetition time after disruption (s)</td>
<td>3’600</td>
</tr>
<tr>
<td>Number of shots per day</td>
<td>5-10</td>
</tr>
<tr>
<td>Days of operation per year</td>
<td>100</td>
</tr>
<tr>
<td>Years of operation</td>
<td>25</td>
</tr>
<tr>
<td>Number of max shots</td>
<td>25’000</td>
</tr>
</tbody>
</table>

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The facility will offer **high flexibility** to test the candidate divertor concepts and to probe different magnetic (i.e. plasma) topologies.

![Diagram showing different magnetic configurations](image)

**Figure I.4**: Single Null (5.5 MA), Double Null (5 MA), Snow Flake (4.5 MA), X-Diverter (4.5 MA), Negative Triangularity (5 MA) and Double Super-X (3 MA) configurations at flat top. The DTT magnetic system is also compatible with a 5 MA long leg configuration. Negative Triangularity and Double Super-X require a dedicated divertor.
Overview of the Superconducting Magnet System
**18 TF coils:**  
**Nb$_3$Sn CICC:** 44.8 kA – 11.9 T  
providing 6.0 T over plasma major radius (2.14 m)  

**6 CS modules** (independently fed)  
**Nb$_3$Sn CICC:** 29 kA – 13.4 T  
providing **16.4 Weber** magnetic flux for plasma initiation at breakdown  

**6 PF coils**  
**Nb$_3$Sn (PF1 & PF6) CICC:** 28.3 kA – 9.1 T  
**NbTi (PF2 to PF5) CICC:** 28.6 kA – 5.4 T  
Identical in pairs to guarantee full top/down symmetry
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SC coils: rationale behind design choices
The design of the DTT superconducting coils in terms of:

- Performance of the superconducting wires (strands)
- Features of the Cable-in-Conduit Conductors (CICC)
- Coil (winding) layout and technologies

is based on

a large experience gained by the scientific fusion community and by industry mainly with the 3 large SC tokamaks

ITER, JT-60SA and K-STAR

and with the high field hybrid magnets of

NHFML, HFML & HZB

in order to minimize R&D phase, for time and cost constraints
### DTT Magnet System

#### MT26 Conference 2019 – Vancouver

- **Ic achieved**: 190 A – 315 A on 0.82 mm wire (Vostner - SUST 2017)
- **Ic achieved**: 325 A on 0.73 mm wire @ 6.4 T (Karasev – IEEE TAS 16)
- **Ic achieved**: > 260 A on 0.82 mm wire (Devred - SUST 2014)

### Min. Critical Current

<table>
<thead>
<tr>
<th>0.82 mm wires</th>
<th>Min. Critical Current <em>(requested by ENEA)</em></th>
<th>Min. Critical Current <em>(guaranteed by the awarded supplier)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DTT TF specs</strong> <em>(Nb_3Sn)</em></td>
<td>285 A <em>(4.2 K; 12 T; 0% strain)</em></td>
<td>300 A <em>(4.2 K; 12 T; 0% strain)</em></td>
</tr>
<tr>
<td><strong>DTT CS &amp; PF1/6 specs</strong> <em>(Nb_3Sn)</em></td>
<td>260 A <em>(4.2 K; 12 T; 0% strain)</em></td>
<td>260 A <em>(4.2 K; 12 T; 0% strain)</em></td>
</tr>
<tr>
<td><strong>DTT PF2-5 specs</strong> <em>(NbTi)</em></td>
<td>500 A <em>(4.2 K; 5 T)</em></td>
<td>NA</td>
</tr>
</tbody>
</table>

Tests *(performed by KAT)* on first samples, gave > 330 A

- **Minimum Critical Current**: Guaranteed by the awarded supplier.

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**DTT TF specs** *(Nb_3Sn)*: 285 A *(4.2 K; 12 T; 0% strain)*

**DTT CS & PF1/6 specs** *(Nb_3Sn)*: 260 A *(4.2 K; 12 T; 0% strain)*

**DTT PF2-5 specs** *(NbTi)*: 500 A *(4.2 K; 5 T)*

**Min. Critical Current (guaranteed by the awarded supplier)**:

- 300 A *(4.2 K; 12 T; 0% strain)*
- 260 A *(4.2 K; 12 T; 0% strain)*
- NA
Superconducting coils design rationale

DTT CICC design is based on the results collected within a number of programs:

Present reference CICC solution based on:
1. rectangular (or square) geometry, with constant thickness steel jacket
2. very short twist pitch cable OR long twist pitch & low Void Fraction
3. Assumption: $\varepsilon_{\text{eff}} = -0.65\%$

Design verification with dedicated experimental tests *(DC properties with e.m. and thermal cycling + AC losses)* is foreseen in the next months, before giving green light to conductor production.
Operative current: 44.8kA
$B_{\text{peak}}$: 11.9 T
Double pancake-winding: 3 rDP; 2 sDP; 80 turns
Max. hydraulic length: 110 m
$\Delta T_{\text{margin}} > 1.4$ K
Turn insulation: Fiber-glass + resin

Wind $\rightarrow$ React $\rightarrow$ Insulation $\rightarrow$ Impregnation

Jacket thickness: 2.0 mm
VF: 26.4%

# Nb$_3$Sn strands: 504
# Cu segregated strands: 144

Nb$_3$Sn strand: 0.82mm diam., Cu/nonCu: 1, RRR=100
Cu segregated strand: 0.82mm diam., RRR $>$ 300
Cr coating: 2 µm

Cabling pattern: (1Cu+2Nb$_3$Sn)+(1Cu+2Nb$_3$Sn)+3Nb$_3$Sn]*3*4*6

Cos-Theta: 0.98 (Long Twist Pitch)

Wrapping: 304L, 0.05mm thick, overlap 30%

Total conductor length (18 coils): ~ 19 km
Total Nb$_3$Sn strand ordered: ~ 55 tons
Total Cu (Cr coated) strand ordered: ~ 15.7 tons
Total 316LN jacket section weight: ~ 30 tons
Simmetric shape of TF coils to allow DN and other possible simmetric scenarios (wrt equatorial plane). All the magnet system weight loads the TF coils. Structures are mainly based on machining of 316L(N) forged sectors.
Toroidal Field Coils - analyses

3D global

2D detailed

Thermal-Hydraulics

3D submodeling

For more details:
G. Romanelli (Wed-Mo-P03.01-02 [2]) & R. Zanino (Wed-Mo-P03.01-03 [3]),
Wednesday poster session

Max $P < 10\text{bar}$
Central Solenoid
Requirements:
- 6 independently fed modules (flexibility)
- Magnetic flux > 16.4 Weber
- Limited room availability (high $J_E$ values)
- Designed to foresee future installation of an insert coil (HTS)

Design choices:
- 6 identical modules
- Layer wound (2 conductor grades)
- Optimized concepts for inter-grade joints and terminations (small curvature radii, small gap between TF and CS,..)
Central Solenoid modules

<table>
<thead>
<tr>
<th></th>
<th>HF (inner) section</th>
<th>LF (outer) section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max operative I</td>
<td>29.04 kA</td>
<td></td>
</tr>
<tr>
<td>Peak field</td>
<td>13.4 T</td>
<td>8.5 T</td>
</tr>
<tr>
<td># s.c. wires</td>
<td>648</td>
<td>180</td>
</tr>
<tr>
<td>Jacket thickn.</td>
<td>4.1 mm</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>Turn insulation</td>
<td>1.0 mm (glass-fiber + resin)</td>
<td></td>
</tr>
<tr>
<td>Ground insulation</td>
<td>6.0 mm (glass-fiber + resin + Kapton)</td>
<td></td>
</tr>
<tr>
<td>Wind &amp; Insulate → React → Impregnate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$J_{\text{ENG}}$ (A/mm$^2$)</td>
<td>26.2</td>
<td>52.2</td>
</tr>
<tr>
<td># layers x turns</td>
<td>6 x 20</td>
<td>8 x 25</td>
</tr>
<tr>
<td>Magnetic Flux</td>
<td>16.4 Wb</td>
<td></td>
</tr>
<tr>
<td>Target $\Delta T_{\text{margin}}$</td>
<td>&gt; 1.0 K</td>
<td></td>
</tr>
<tr>
<td>Max. voltage</td>
<td>3.5 kV (terminal to terminal)</td>
<td></td>
</tr>
</tbody>
</table>
Stress level in SS is below the allowable limits for both components: membrane (667 MPa) and membrane + bending (867 MPa).

For more details: L. Giannini (Wed-Mo-Po3.01-05 [5]), Wednesday poster session.
Poloidal Field coils
### Poloidal Field Coils

- **6 independent coils**
- On PF1&6 max B around 9T $\rightarrow$ Nb$_3$Sn strands
- Designed identical in pairs for symmetry

<table>
<thead>
<tr>
<th></th>
<th>PF1/6</th>
<th>PF2/5</th>
<th>PF3/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{\text{max}}$ (T) (input data)</td>
<td>9.1</td>
<td>4.2</td>
<td>5.3</td>
</tr>
<tr>
<td>R (mm)</td>
<td>1416</td>
<td>3068</td>
<td>4335</td>
</tr>
<tr>
<td>$\pm \Delta R$ (mm)</td>
<td>542</td>
<td>302</td>
<td>422</td>
</tr>
<tr>
<td>Z (mm)</td>
<td>$\pm 2760$</td>
<td>$\pm 2534$</td>
<td>$\pm 1015$</td>
</tr>
<tr>
<td>$\pm \Delta Z$ (mm)</td>
<td>590.4</td>
<td>516.8</td>
<td>452.2</td>
</tr>
<tr>
<td>Ground Insulation</td>
<td>5mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td># turns (radial)</td>
<td>20</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td># turns (vertical)</td>
<td>18</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>Total N turns</td>
<td>360</td>
<td>160</td>
<td>196</td>
</tr>
<tr>
<td>$I_{\text{op max}}$ (kA)</td>
<td>28.3</td>
<td>27.1</td>
<td>28.6</td>
</tr>
<tr>
<td>$\Delta T_{\text{margin}}$ ($T_{\text{op}}$: 4.5K)</td>
<td>1.8</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>L (H)</td>
<td>0.454</td>
<td>0.298</td>
<td>0.690</td>
</tr>
<tr>
<td>$V_{\text{max}}$ (V)</td>
<td>2150</td>
<td>1350</td>
<td>3290</td>
</tr>
<tr>
<td>Weight (tons)</td>
<td>15</td>
<td>16</td>
<td>28</td>
</tr>
<tr>
<td>delay / discharge constant</td>
<td>1.5 s / 6 s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Less room is available for joints & terminations of PF1/6 → 1 support each 2 TF coils

For more details: S. Turtù (Wed-Mo-Po3.01-01 [1]), Wednesday poster session
For more details: L. Zoboli (Wed-Mo Po3.01-04 [4]), Wednesday 1.45pm poster session.
Side projects/activities
Technical merits:
- Higher Magnetic Flux (16.4 Volt sec $\rightarrow$ 17.3 Volt sec)
- Higher Magnetic Field (14 T $\rightarrow$ 17.5 T)
- Fundamental technology demonstration toward high-magnetic field fusion.

For more details:
A. Zappatore (Mon-Mo-Or3.06)
today 12.30
ENEA decided to create a new infrastructure in Frascati

18 TF coils + 7 CS modules + PF1 & 6 will be tested at 4.5K

Current leads, Power Supply & Quench protection prototypes will be used for cold tests and thus qualified against real conditions

This activity is in addition to the DTT budget (ENEA’s investment only)

Adaptation of the Superconductivity lab to host the new facility is already started
Planning & current status
1/3 of the machine must be completed by 2022 (6 TFCs, 3 VV sectors, cryostat base, main hall, ...)

Commissioning of the machine shall be completed within 2025

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Start</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTT project</td>
<td>Fri 21/12/18</td>
<td>Wed 25/02/20</td>
</tr>
<tr>
<td>Strands Market Survey launched</td>
<td>Fri 21/12/18</td>
<td>Fri 21/12/18</td>
</tr>
<tr>
<td>DRB+1</td>
<td>Thu 10/01/19</td>
<td>Thu 16/01/19</td>
</tr>
<tr>
<td>PROJECT MILESTONES</td>
<td>Mon 30/11/19</td>
<td>Fri 05/12/25</td>
</tr>
<tr>
<td>DTT-M1 - DEMONSTRATION THAT REMAINING FABRICATION WILL BE COMPLETED AT LOW RISK</td>
<td>Wed 13/12/19</td>
<td>Wed 04/01/23</td>
</tr>
<tr>
<td>DTT-M2 - DEMONSTRATION THAT ASSEMBLY WILL BE COMPLETED AT LOW RISK</td>
<td>Thu 09/05/22</td>
<td>Wed 21/12/22</td>
</tr>
<tr>
<td>DTT-M3 - DEMONSTRATION THAT MACHINE CAN BE COMMISSIONED SUCCESSFULLY</td>
<td>Wed 09/05/21</td>
<td>Wed 09/05/21</td>
</tr>
<tr>
<td>DTT-M4 - DEMONSTRATION THAT THE FINANCIAL AND HUMAN RESOURCES ARE AVAILABLE FOR PROJECT COMPLETION</td>
<td>Fri 30/11/22</td>
<td>Fri 30/11/22</td>
</tr>
<tr>
<td>COMM-M5 - DTT-Trial Design Consistent with the Requirements for Testing Alternate Exhaust Concepts Based on the Knowledge at the Time</td>
<td>Wed 30/11/19</td>
<td>Wed 30/11/19</td>
</tr>
<tr>
<td>COMM-M6 - DECISION ON THE FIRST ID0 DIVERTOR</td>
<td>Fri 30/11/22</td>
<td>Fri 30/11/22</td>
</tr>
<tr>
<td>COMM-M3 - ASSESSMENT OF THE INFRASTRUCTURE AND EXHAUST INFRASTRUCTURE AND DIAGNOSTIC OPPORTUNITIES IN DTT</td>
<td>Fri 30/11/22</td>
<td>Fri 30/11/22</td>
</tr>
<tr>
<td>PROM-MS-99 START OF INTEGRATED COMMISSIONING</td>
<td>Mon 20/05/22</td>
<td>Mon 20/05/22</td>
</tr>
<tr>
<td>PROM-MS-95 FIRST PLASMA</td>
<td>Fri 05/12/22</td>
<td>Fri 05/12/22</td>
</tr>
</tbody>
</table>

- **01 - PHYSICS**
  - MAG-41 TFC
  - MAG-42 C COILS
  - MAG-43 P COILS
  - MAG-44 CURRENT LEADS & CL BOXES
  - MAG-45 STRANS & CONDUCTORS
  - MAG-46 50 feeders
  - MAG-47 In Vessel Cpl CONDUCTORS
  - MAG-48 GRENCH PROTECTION SYSTEM
  - MAG-49 COLD TEST FACILITY
  - ARC - MECHANICAL STRUCTURES
  - 04 - HCD - HEATING AND CURRENT DRIVE
  - 05 - AUXILIARY PLANT SYSTEMS
  - 06 - PSS - Power Supply Systems
  - 07 - BBU - Building Layout and Services
  - 08 - DCS DIAGNOSTICS & CONTROL SYSTEMS
  - 09 - SLE SYSTEM LEVEL ENGINEERING
The project has been officially **financed and kicked-off.** The machine is being built at the Frascati Research Center of ENEA (Italy), where FTU is currently being de-commissioned and disassembled.

DTT Scrl legal entity (to manage DTT procurement and operation) has been settled.

- To accomplish the **tight schedule the short term planning is:**
  - **Strand supply partly assigned** (≈ 77 tons of Nb3Sn, ≈ 27 tons of NbTi, ≈ 50 tons of Cu)
  - 10/2019: Conductor procurement tender
  - Within the end of 2019: TF Winding Pack & Integration - TF case and structures (2 different tenders)
  - Early 2020: PF coils / CS coils / SC current leads & Feeders Tenders
THANKS FOR YOUR ATTENTION!

Grazie!

INFO DAY
FOR THE PROCUREMENT OF THE DTT TOROIDAL MAGNETS

October 8, 2019
Bruno Brunelli Hall, ENEA Frascati

https://agenda.enea.it/event/211/overview
Backup slides
6 independent coils
On PF1&6 max B around 9T → Nb$_3$Sn strands
Designed identical in pairs for symmetry

<table>
<thead>
<tr>
<th>Conductor</th>
<th>PF1/6</th>
<th>PF2/5</th>
<th>PF3/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial Ext. Dim. (mm)</td>
<td>23.4</td>
<td>26.4</td>
<td>26.4</td>
</tr>
<tr>
<td>Vertical Ext. Dim. (mm)</td>
<td>28.2</td>
<td>27.7</td>
<td>27.7</td>
</tr>
<tr>
<td>Jacket thickness (mm)</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Inner Corner Radius (mm)</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Central Channel (OD/ID; mm)</td>
<td>7/5</td>
<td>7/5</td>
<td>7/5</td>
</tr>
</tbody>
</table>

Inter-turn insulation (mm)
- turn insulation should consist of layers of interleaved kapton and fiberglass.
- 1.8mm turn insulation thickness is conservative, to have a big margin making a turn-to-turn and DP-to-DP insulation fault very unlikely
- analyses to evaluate voltage values in normal and faulted conditions are on going

# SC strands (0.82mm)
180 (Nb$_3$Sn)
162 (NbTi)
324 (NbTi)

Strand Cu no-Cu ratio
1
1.9
1.9

# Cu strands (0.82mm)
216
324
162

Total strand number
396
486
486

Cabling sequence
[2x(2sc+Cu)x(8+Cu core)x6 Cu core: 12 strand (2Cu+15C)x3x3x3x6 (1Cu+2Cu)x3x3x3x6

Void fraction
29.9% (*)
30.2%
30.2%

LBO wrapping
(0.05 ± 0.01) mm x 12 mm, open area 50%, SS
(0.05 ± 0.01) mm x 40mm, 50% overlapping, SS
DTT wrt other superconducting Tokamaks

**JT-60SA** ($B_T = 2.25$ T, $I_p = 5.5$ MA)

- **ITER** ($B_T = 5.3$ T, $I_p = 15$ MA)
  - 25.7 kA - 5.7 T NbTi

- **KSTAR** ($B_T = 3.5$ T, $I_p = 2$ MA)
  - 68.0 kA - 12 T Nb$_3$Sn

- **DTT** ($B_T = 6$ T, $I_p = 5.5$ MA)
  - 35.2 kA - 7.2 T Nb$_3$Sn
  - 44.8 kA - 11.9 T Nb$_3$Sn
ENEA-TRATOS Aluminum slotted Core HTS CICC

Most recent concept

External high-strength Aluminum-alloy jacket.

\[ L = 36 \text{ mm} \]

6 slots for twisted stack of s.c. tapes

30 \text{ – } 35 \text{ kA} \text{ current in } 18 \text{ T} \text{ – } 20 \text{ T field}

(to be tested)
- **$\text{Nb}_3\text{Sn}$** performance depends (strongly) on strain state and sensitivity is **hard to predict**;
- $\text{Nb}_3\text{Sn}$ wire inside Cable-in-Conduit conductors (CICC) is subject to **strain**:

From: Breschi_SUST 2017
S.C. components design rationale: CICC