The DTT device: Poloidal Field Coil Assessment for Alternative Plasma Configurations

R. Ambrosino on behalf of the project team
Summary

- Requirements on the PF coils system
- DTT Reference Single Null scenario
- DTT Alternative configurations
- Use of in-vessel coils
- Conclusions
Requirements on the PF coils system

PF coil currents and voltages

The PF voltage and current limits are reported below

<table>
<thead>
<tr>
<th>Name</th>
<th>I_{sat} (kA)</th>
<th>V_{sat} (V)</th>
<th>Turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS3U</td>
<td>23</td>
<td>800</td>
<td>270</td>
</tr>
<tr>
<td>CS2U</td>
<td>23</td>
<td>800</td>
<td>420</td>
</tr>
<tr>
<td>CS1U</td>
<td>23</td>
<td>800</td>
<td>420</td>
</tr>
<tr>
<td>CS1L</td>
<td>23</td>
<td>800</td>
<td>420</td>
</tr>
<tr>
<td>CS2L</td>
<td>23</td>
<td>800</td>
<td>420</td>
</tr>
<tr>
<td>CS3L</td>
<td>23</td>
<td>800</td>
<td>270</td>
</tr>
<tr>
<td>PF1</td>
<td>25.2</td>
<td>800</td>
<td>130</td>
</tr>
<tr>
<td>PF2</td>
<td>22.6</td>
<td>800</td>
<td>108</td>
</tr>
<tr>
<td>PF3</td>
<td>21.2</td>
<td>1000</td>
<td>112</td>
</tr>
<tr>
<td>PF4</td>
<td>24.7</td>
<td>1000</td>
<td>140</td>
</tr>
<tr>
<td>PF5</td>
<td>23</td>
<td>800</td>
<td>152</td>
</tr>
<tr>
<td>PF6</td>
<td>23.3</td>
<td>800</td>
<td>260</td>
</tr>
<tr>
<td>C1</td>
<td>60</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>C2</td>
<td>60</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>C3</td>
<td>60</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>C4</td>
<td>60</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>C5</td>
<td>25</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>C6</td>
<td>25</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>C7</td>
<td>60</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>C8</td>
<td>60</td>
<td>50</td>
<td>1</td>
</tr>
</tbody>
</table>

Magnetic field

The maximum magnetic field at the location of the CS coils shall not exceed 12.5 T. The constraint related to the magnetic field is not stringent for the PF coils. A posteriori, it was verified that its maximum value is about 4.0 T in PF6.
Requirements on the PF coils system

*Vertical Forces*

The force limits on the PF coils have been scaled from DEMO constraints and verified on DTT geometry. We assume the force scaling with the square of the major radius $R$ resulting in a factor for the force limit of 17 with respect to DEMO.

- The maximum vertical force on the CS stack in DTT should not exceed 17 MN
- The maximum separation force in the CS stack should not exceed 20 MN
- Maximum vertical force on a single PF coil should not exceed 26MN

*Plasma*

- Minimum distance of 40 mm between the plasma last closed surface and the first wall, in order to minimize the interaction between the plasma and the main chamber
- The maximum plasma current is 6 MA, whereas the plasma shape parameters should be similar to the present EU design of DEMO, with an aspect ratio $R/a\approx3.1$, an elongation $k\approx1.75$. 
Reference Single Null scenario

The reference Single Null scenario has been designed to build-up the X-point configuration at $I_{pl} = 6\,\text{MA}$ in H-mode.

**Ramp-up (0s-32s)**
- *Limiter phase* 0s-15s with $I_{pl} \approx 3\,\text{MA}$
- *Xpoint formation* between 15s -23s with $I_{pl} \approx 4.3\,\text{MA}$
- *Diverted phase* 23—32s with $I_{pl}$ reaching 6 MA
- *Full additional heating* at $t = 32\,\text{s}$

**Flat top (32s-100s)**
After $t = 42\,\text{s}$, all plasma physical parameters are assumed to remain nearly constant up to the end of the current plateau.
Reference Single Null scenario

The present SN configuration at \( I_{pl} = 6MA \) has an average divertor leg of about 25cm. The possibility to increase the X-point-divertor distance is also possible in DTT working on

1. the magnetic configuration, with a reduction of the plasma current to \( I_{pl} = 5MA \) and a plasma volume \( V_{pl} = 32m^3 \) (instead of \( 39m^3 \) of the reference scenario at flat top)

2. the divertor design, assuming a ADX like divertor

<table>
<thead>
<tr>
<th></th>
<th>( L_a(cm) )</th>
<th>( L/a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADX</td>
<td>( \approx 30 )</td>
<td>( \approx 1 )</td>
</tr>
<tr>
<td>DEMO (A=3.1 2015)</td>
<td>( \approx 130 )</td>
<td>( \approx 0.45 )</td>
</tr>
<tr>
<td>DTT 6 MA</td>
<td>( \approx 25 )</td>
<td>( \approx 0.35 )</td>
</tr>
<tr>
<td>DTT 5 MA</td>
<td>( \approx 35 )</td>
<td>( \approx 0.55 )</td>
</tr>
<tr>
<td>DTT 5 MA (ADX-like div.)</td>
<td>( \approx 65 )</td>
<td>( \approx 1 )</td>
</tr>
</tbody>
</table>
Alternative configurations that can be obtained using the DTT PF system:

**Snowflake (SF)** with $I_{pl} = 5.5\, MA$

**Double null (DN)** with $I_{pl} = 5\, MA$

**Single null with reverse triangularity (RT)** with $I_{pl} = 5\, MA$

**Super-X (SX)** with $I_{pl} = 3\, MA$

- The design of divertor structures compatible with all the configurations is under analysis (*see Presentation of Giuseppe Di Gironimo*)
An outer long leg configuration has been designed assuming

- Plasma current \( I_{pl} = 3\, MA \)

- \( \frac{R_{\text{target}}}{R_{\text{point}}} \approx 1.6 \rightarrow \frac{B_{\text{point}}}{B_{\text{target}}} \approx 1.6 \) (similar to DEMO)

- Plasma volume of \( V_{SX} \approx 20\, m^3 \) \( (V_{SN} \approx 39\, m^3) \)

The possibility to add a couple of in-vessel coils in the vicinity of the divertor plate is under analysis for the definition of a Super-X configuration.

The current estimation for the in-vessel coils \( (I = B_{pol} \, d_{\text{coils}} \, 2\pi / \mu_0) \) is:

- \textbf{DTT with In-vessel coils distance of} \( d_{\text{coils}} \approx 20cm \) \( \Rightarrow I \approx 500kA \)

- \textbf{DEMO with In-vessel coils distance of} \( d_{\text{coils}} \approx 100cm \) \( \Rightarrow I \approx 2.5\, MA \)
Snowflake plus configuration at $I_{pl}=5.5\,\text{MA}$ has been designed assuming:

- SF point position in the vicinity of the SN X-point
- Distance between the active and not active X-points $<20\,\text{cm}$
- SF volume similar to the SN volume
- No use of internal coils
- Maximum vertical force on the PF coils $\leq 30\,\text{MN}$

<table>
<thead>
<tr>
<th>Configuration</th>
<th>SN</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_p, [\text{MA}]$</td>
<td>6</td>
<td>5.5</td>
</tr>
<tr>
<td>Flux swing at flat top [Vs]</td>
<td>10.11</td>
<td>6.5</td>
</tr>
<tr>
<td>Plasma volume (m$^3$)</td>
<td>39</td>
<td>38</td>
</tr>
<tr>
<td>Elongation $k_{95%}$</td>
<td>1.67</td>
<td>1.78</td>
</tr>
<tr>
<td>growth rate [ s$^{-1}$]</td>
<td>$\sim40$</td>
<td>$\sim40$</td>
</tr>
</tbody>
</table>

With the use of the in-vessel coils, it will be also possible to adjust a second null region in SF, obtaining a large area where the poloidal field and its gradient are close to zero.
Use of in-vessel coils: from SF+ to SF-

Internal copper coils can be used for plasma control or local modifications of the magnetic configuration in the divertor region.

Snowflake minus with a distance between the X-points within 10cm can be obtained assuming a maximum current in the in-vessel coils of 60kA:

\[
C1 = +33kA \\
C2 = -37kA \\
C3 = -23kA \\
C4 = +38kA
\]
Use of in-vessel coils: form SF+ to XD

Internal copper coils can be used to pass from a relaxed SF+ configuration with a distance between the X-points around 50cm to a XD configuration.

XD can be obtained assuming a maximum current in the in-vessel coils of 60kA:

\[ C1 = +29kA \]
\[ C2 = -60kA \]
\[ C3 = -1kA \]
\[ C4 = +50kA \]
The accuracy of the null-point control is critical for an ideal-SF configuration due to the effect of poloidal field variation in the SF point region.

Distance between the X-points in the SF configuration as a function of the constant poloidal field variation

While, a magnetic field variation of 1-5mT have a significant effect in the SF-point region in case of ideal-SF, they turn out to be marginal when the initial distance between the X-points is of the order of 10-20cm.
Conclusions

- In this presentation the SN scenario at 6MA for the DTT tokamak has been illustrated.

- **Alternative configurations** such as:
  - **Snowflake plus** at 5.5MA
  - **Double Null** at 5MA
  - **Super-X** at 3MA

  can be achieved on DTT without the support of the internal coils.

- **With the use of the in-vessel coils**, it will be also possible to adjust a second null region of the reference configurations, obtaining a large area where the poloidal field and its gradient are close to zero. Possible configurations achieved with invessel coils are:
  - **X-Divertor**
  - **Snowflake minus**
Conclusions: answers to PEX questions

1. ... From the plots in Chapter 3, it looks like the divertor legs will always be relatively short (in poloidal cross-section) compared to, e.g., ADX equilibria. If a long-legged divertor turns out to be the optimum, what kind of equilibrium can be run and how would that impact on plasma current, volume and performance?

The possibility to increase the X-point-divertor distance is possible in DTT working on

- the magnetic configuration, with a reduction of the plasma current to $I_{pl} = 5MA$ and a plasma volume $V_{pl} = 32m^3$ (instead of $39m^3$) of the reference scenario at flat top
- the divertor design, assuming a ADX like divertor

5. What is the maximum value of $B(x\text{-pt})/B(target)$, also for a DN (S)XD configuration?

For the Super-X configuration $B(x\text{-pt})/B(target) \approx 1.6$ (similar to DEMO SX) while for the other DTT configuration $B(x\text{-pt})/B(target) \approx 1.1$.

6. Snowflake divertor
   a. What is the smallest achievable distance between the two null-points of a snowflake divertor?
   b. What is the predicted accuracy of the null-point control?

With the use of the invessel coils the distance between the two null-points can be optimized with very small IC currents. However, the sensitivity of an ideal SF to magnetic field variations is significant